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Title: HEAT TRANSFER SCOPING CALCULATIONS

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Intended for: Report

Issued: 2019-06-20

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Heat Transfer Scoping Calculations

Nick Wynne

June 5, 2019

Abstract

This set of slides summarizes calculations done to bound heat transfer from inner metallic shells of variable thicknesses, through an outer polymeric shell, and ultimately to the external world. Two initial conditions were studied. The first condition provides a constant thermal power (energy per unit time) to the first inner shell and calculates thermal equilibrium. The second condition establishes an initial temperature of 640 Celsius in the first inner shell, and then models the heat transfer as a function of time through the outer shell and then to the surroundings. Conservative assumptions about the conduction between shells and the natural convection or radiation to the surroundings were used to bound or to scope the range of solutions. This is an idealized, one-dimensional, system of three materials and the bounding environment calculated as a two-dimensional axisymmetric problem in COMSOL to determine the feasibility of using such a model on more complex systems, in higher dimensions.

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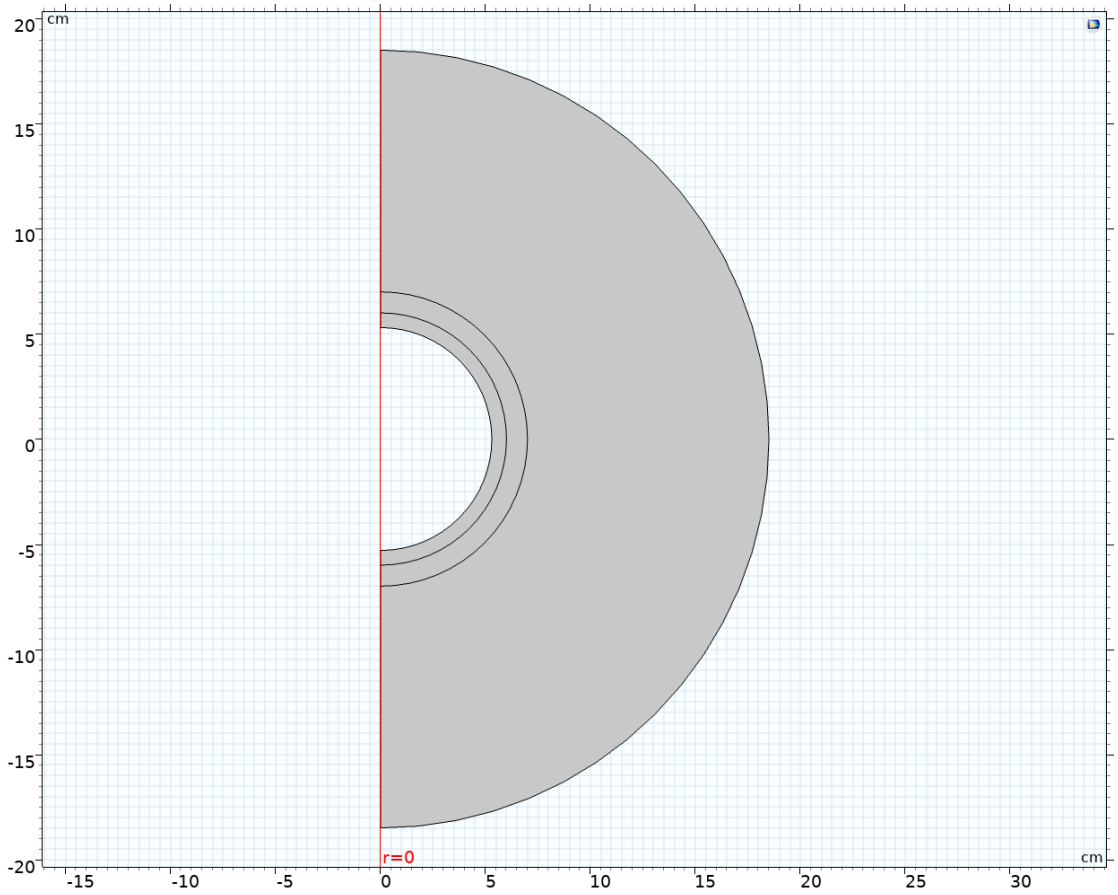
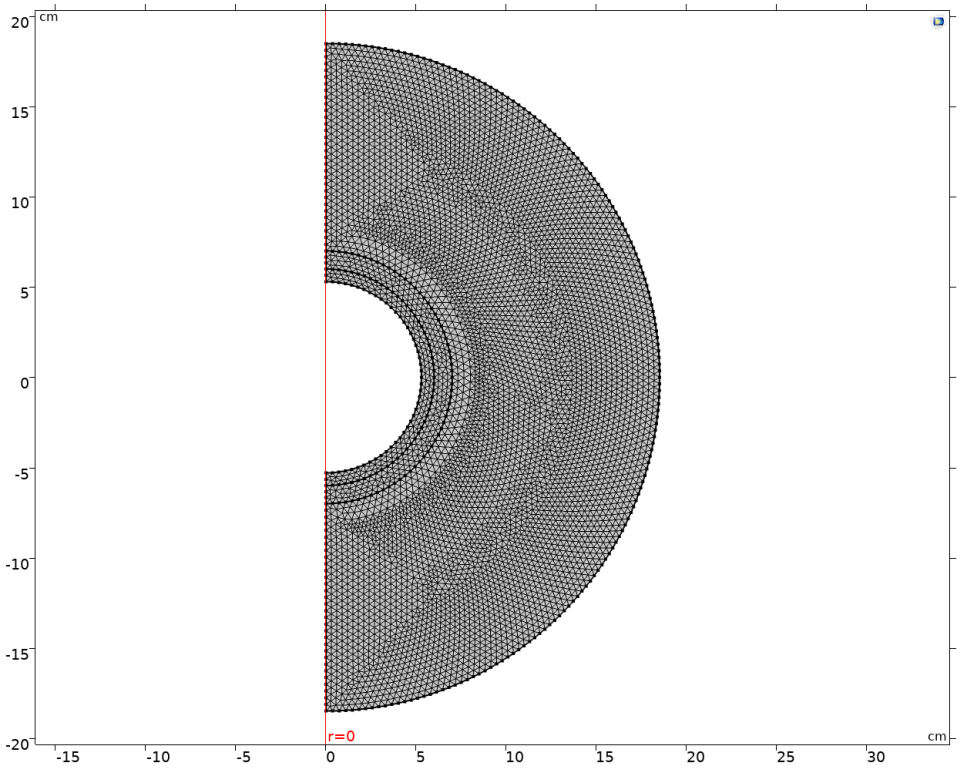
Case 1 - 4 Geometry

- 2D Axisymmetric
- Shell 1
  - Inner radius = 5.3 cm
  - Outer radius = 6.0 cm
- Shell 2
  - Inner radius = 6.0 cm
  - Outer radius = 7.0 cm
  - No air gap with shell 1 for cases 1, 2, 3, & 3b. Air gap (.0254 cm) is present for cases 2c & 4.
- Shell 3
  - Inner radius = 7.0 cm
  - Outer radius = 18.5 cm
  - No air gap (.0254 cm) with shell 2 for cases 1, 2, 3, & 3b. Air gap is present for cases 2c & 4.



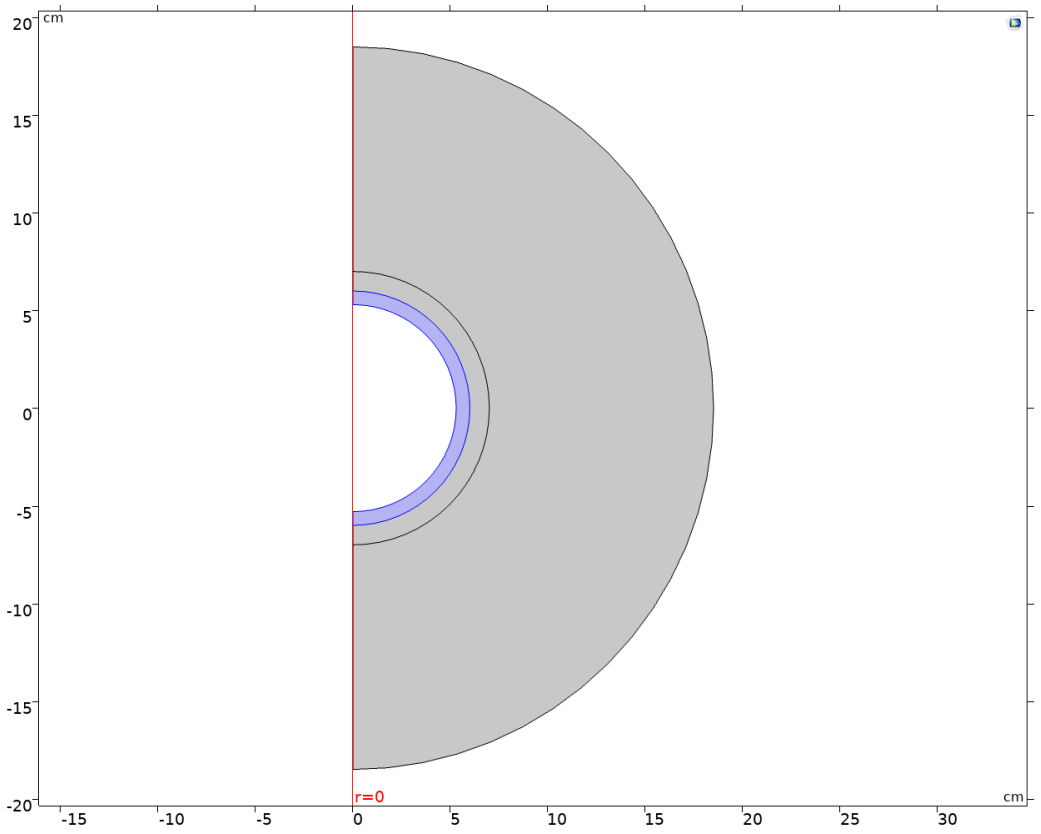
Case 1, 2, & 3 Assumptions

- 600W uniformly distributed in shell 1
- No radiation heat transfer between shells
- The outer surface of shell 3 is a blackbody→ Perfect Emitter to surroundings
- All solid materials→ No phase change
- Isotropic thermal conductivity
- No thermal expansion
- Natural convection with air or water
- Laminar boundary layers
- Same mesh used for all cases



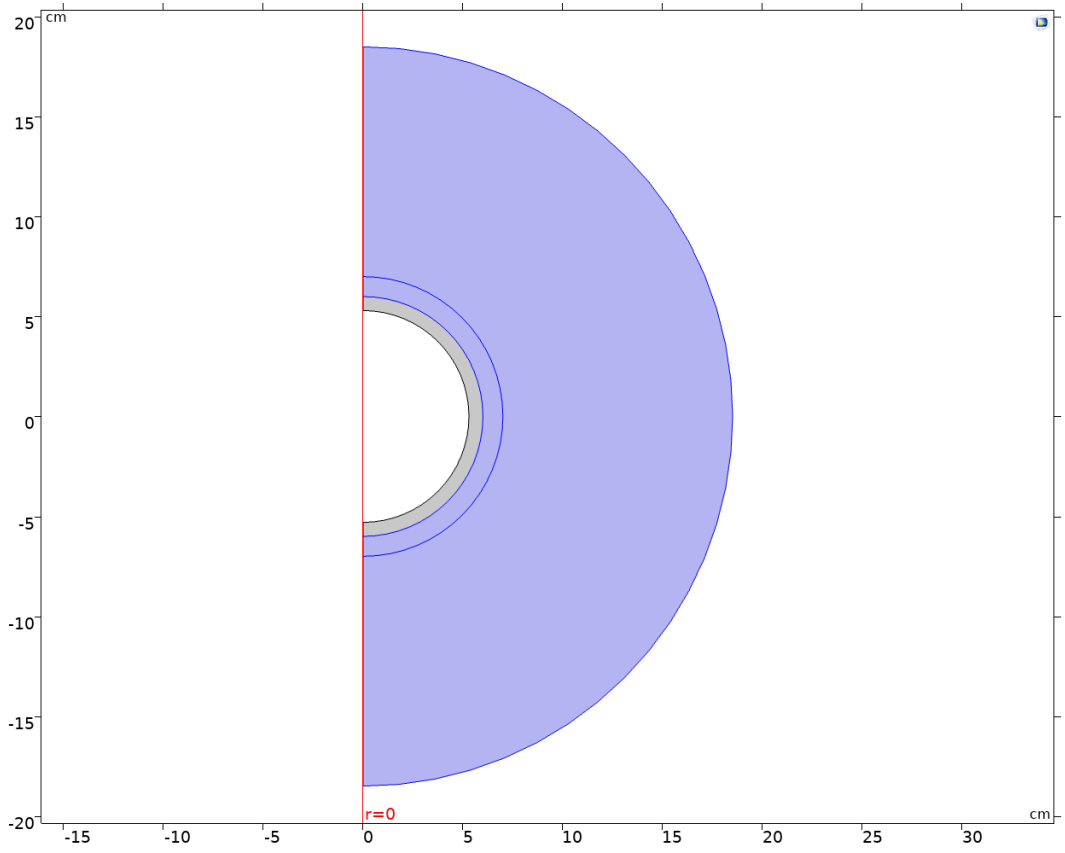
Case 1 Materials

- Stainless Steel 304
  - Solid (no phase change)
  - k(T)
  - cp(T)
  - Density (T)
  - Source: COMSOL Material Library



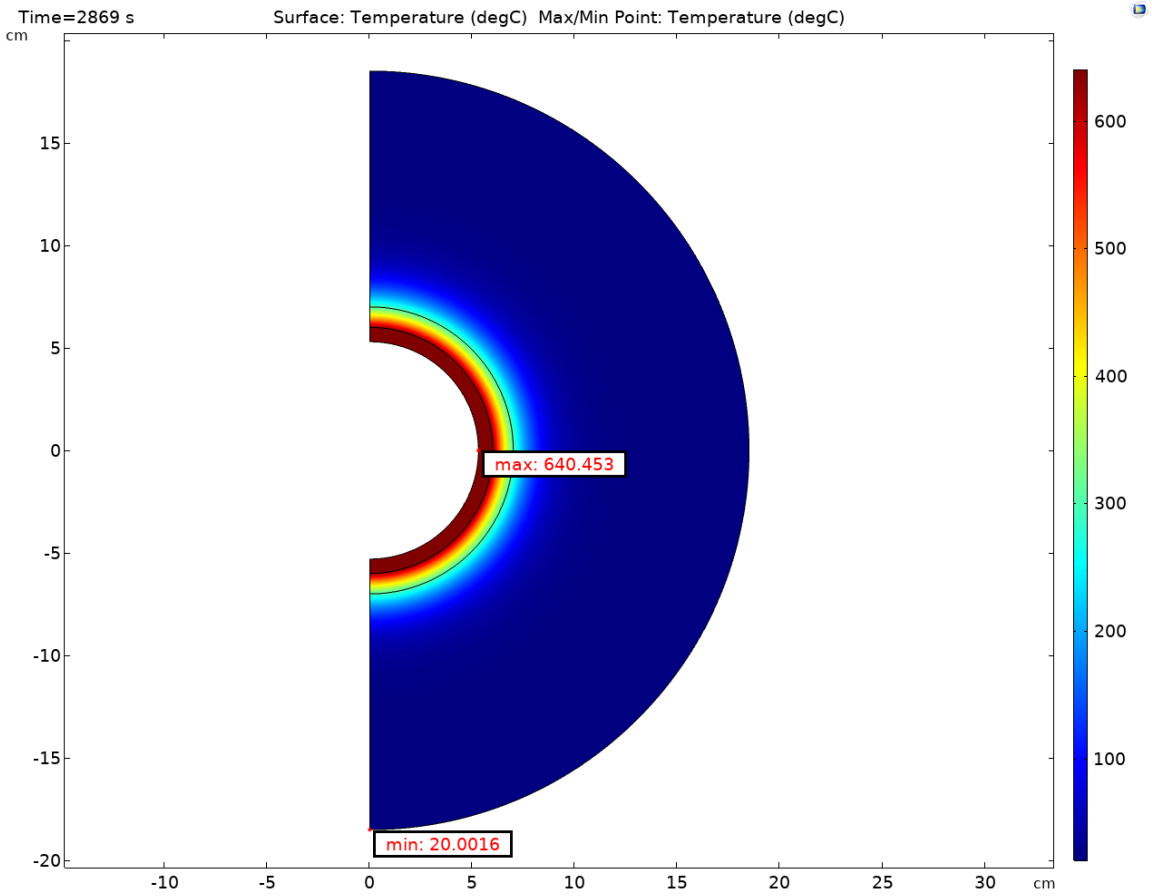
Case 1 Materials

- HDPE
  - Solid (no phase change)
  - k(T)
  - Density(T)
  - Constant cp
    - 2.25 J/g*degC
  - Source: COMSOL Material Library

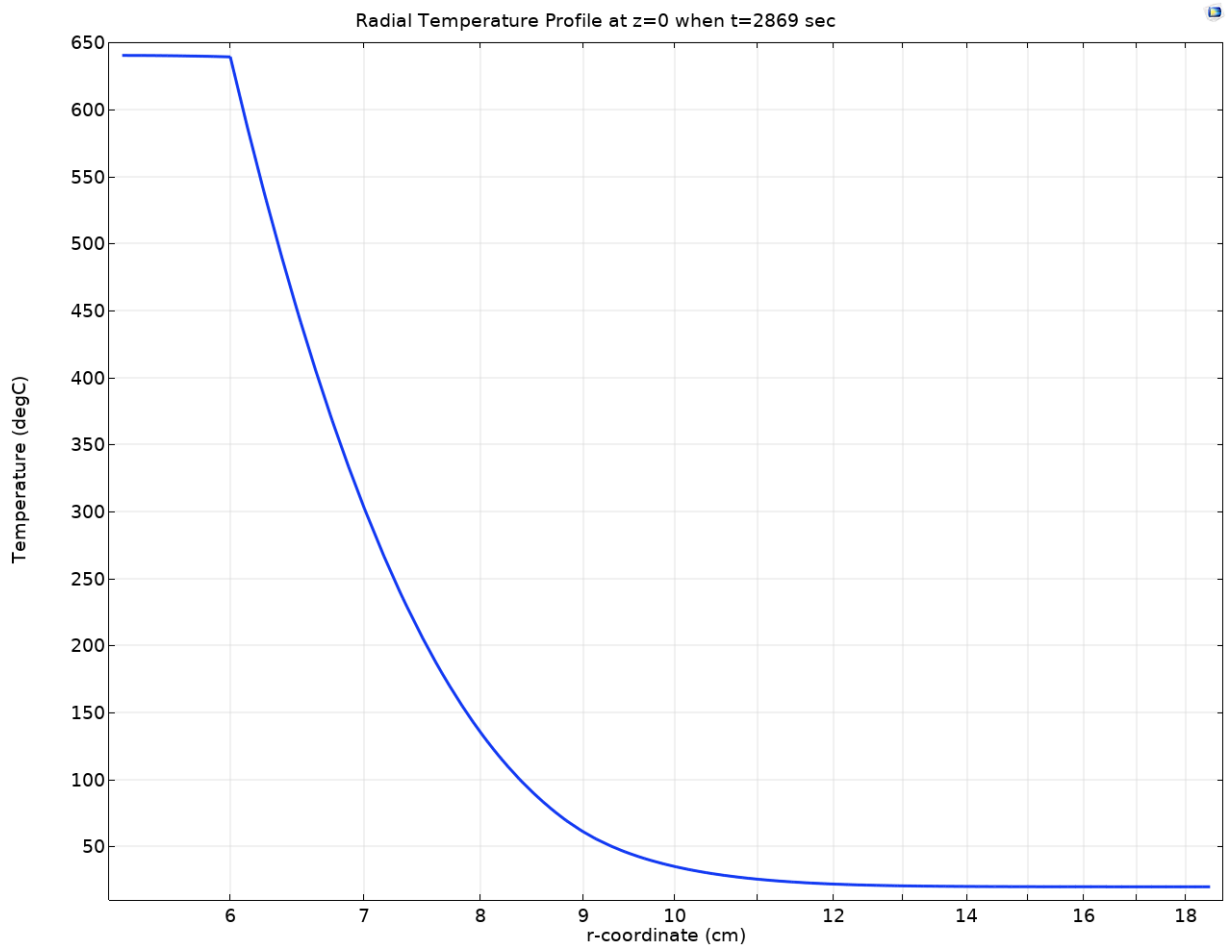


Results: Case 1- Air, Transient

- Transient Run
- Shell 1 Tavg= 640.00 degC at t=2869 sec.
- Outer surface of shell 3 does not heat up yet.
- We would have localized melting in the HDPE before the stainless reaches 640 degC. I would expect shell 1 to translate down into the melt and no longer be concentric with the surrounding shells.
- HDPE Tmelt = 135 degC

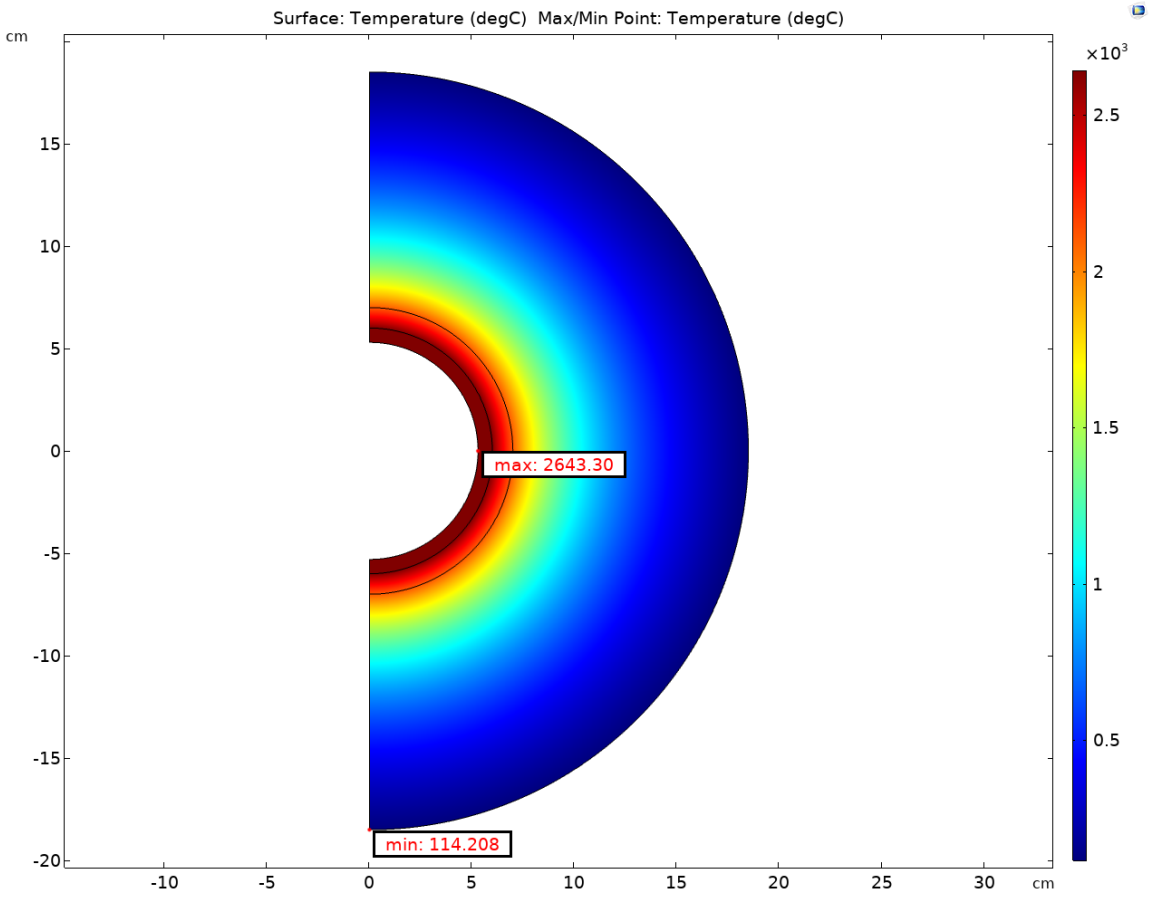


Results: Case 1- Air



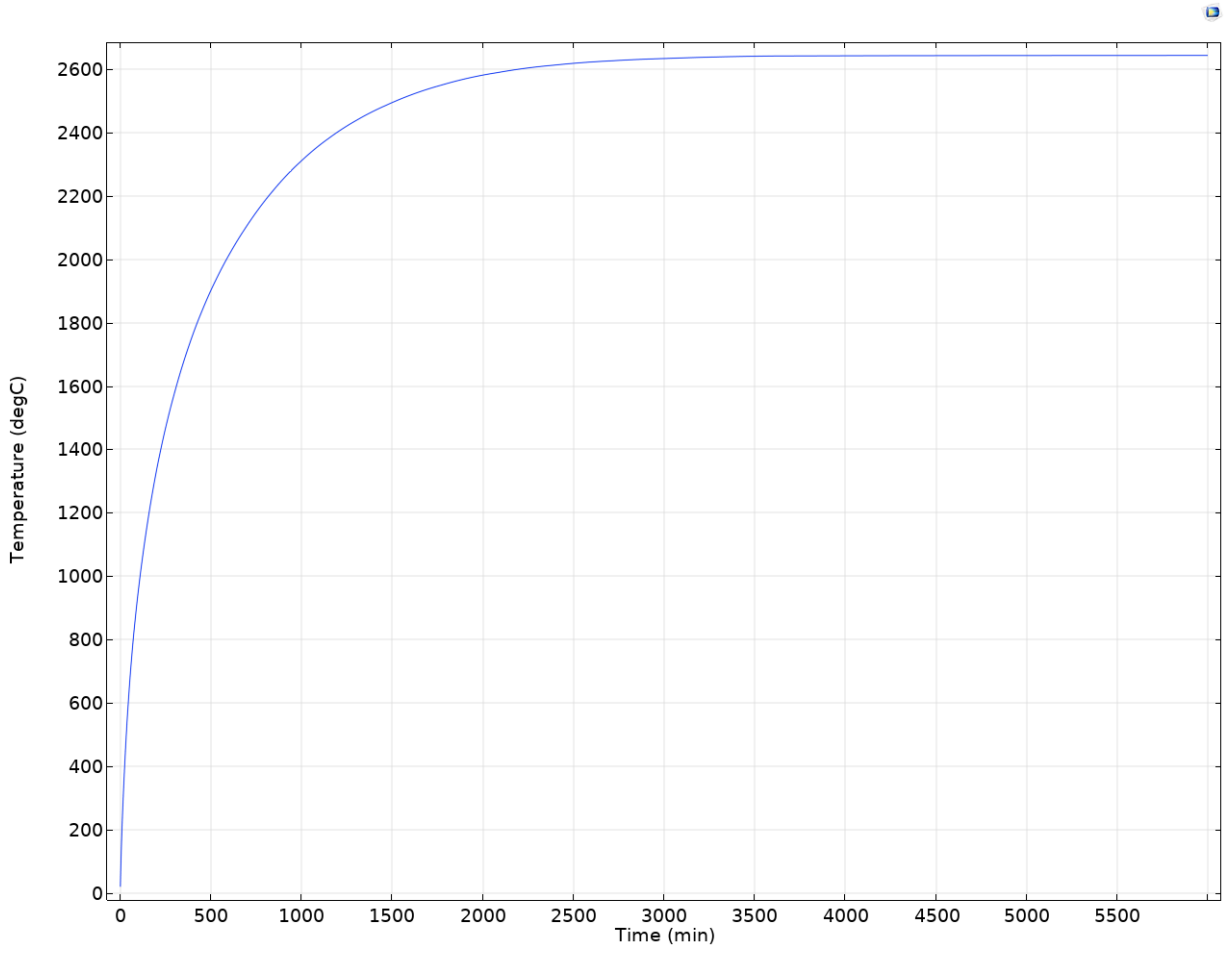
Results: Case 1 – Air, Steady State

- Steady State Results for reference.
- Compares well with analytical results (hand calc)
- ~3000 min = 50 hours to reach steady state (see next slide)



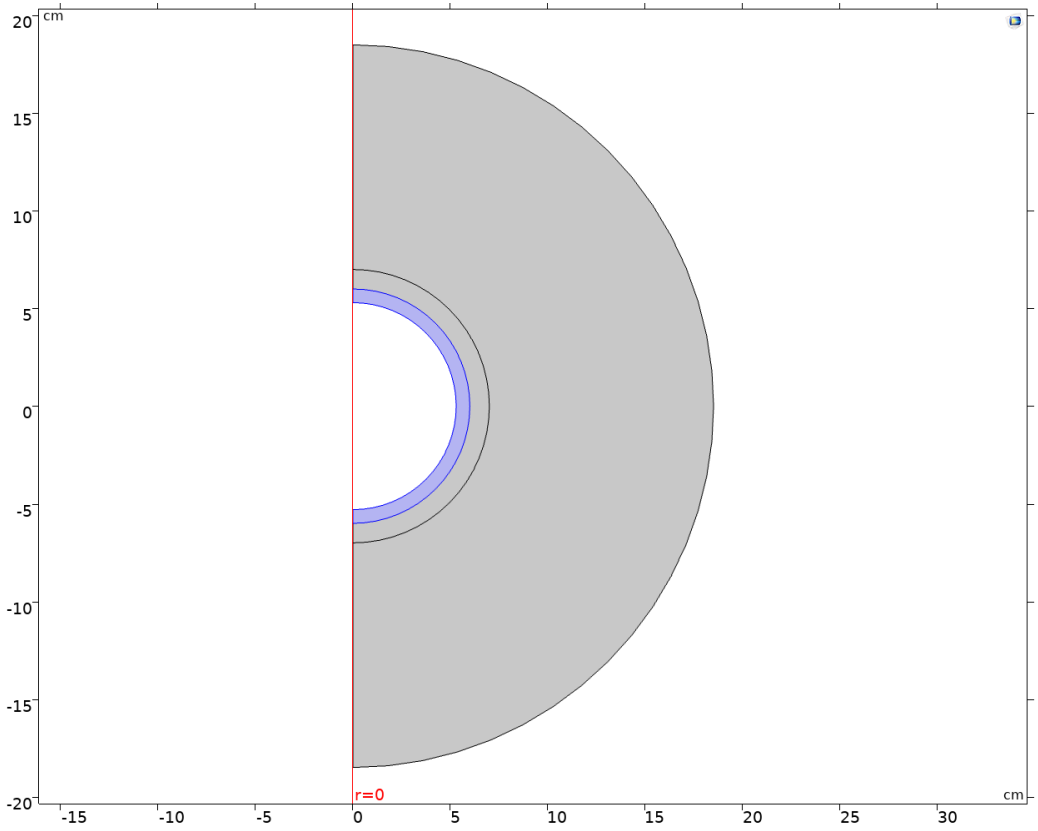
Results: Case 1- Air

- Average Temperature in Shell 1 vs Time



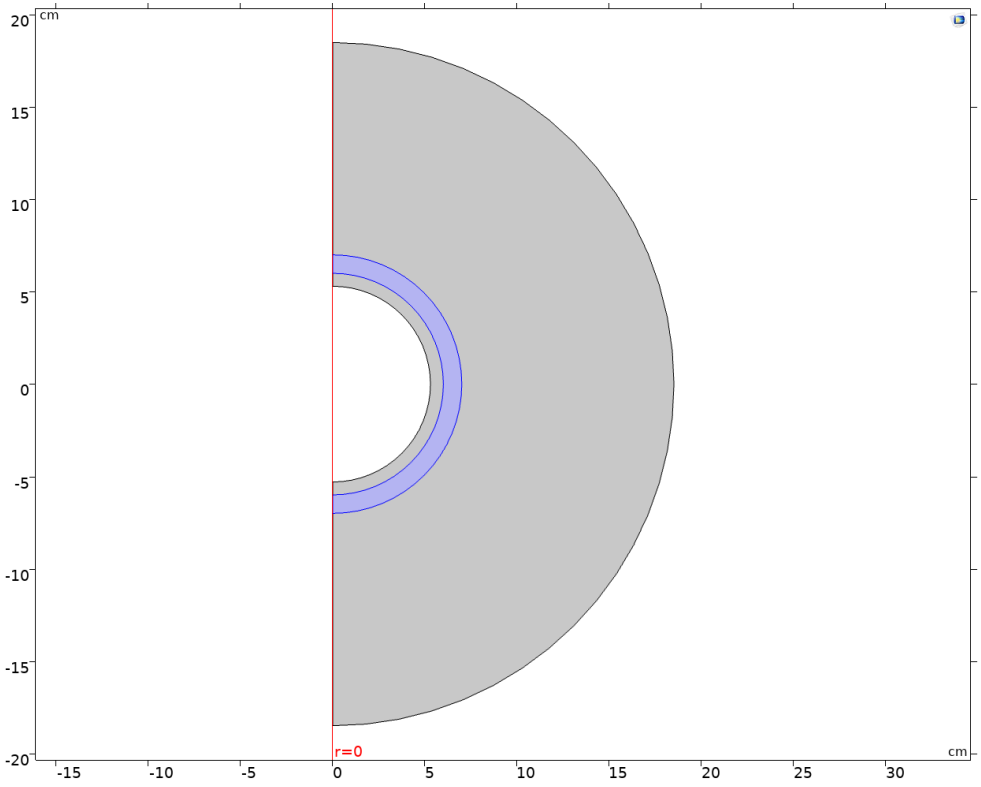
Case 2 Materials

- Fuel 1
  - Solid (no phase change)
  - Room temp solid phase used
  - k=constant
  - cp(T)
  - Density (T)
  - Source: AAA Fuels Handbook, Kim and Hofman



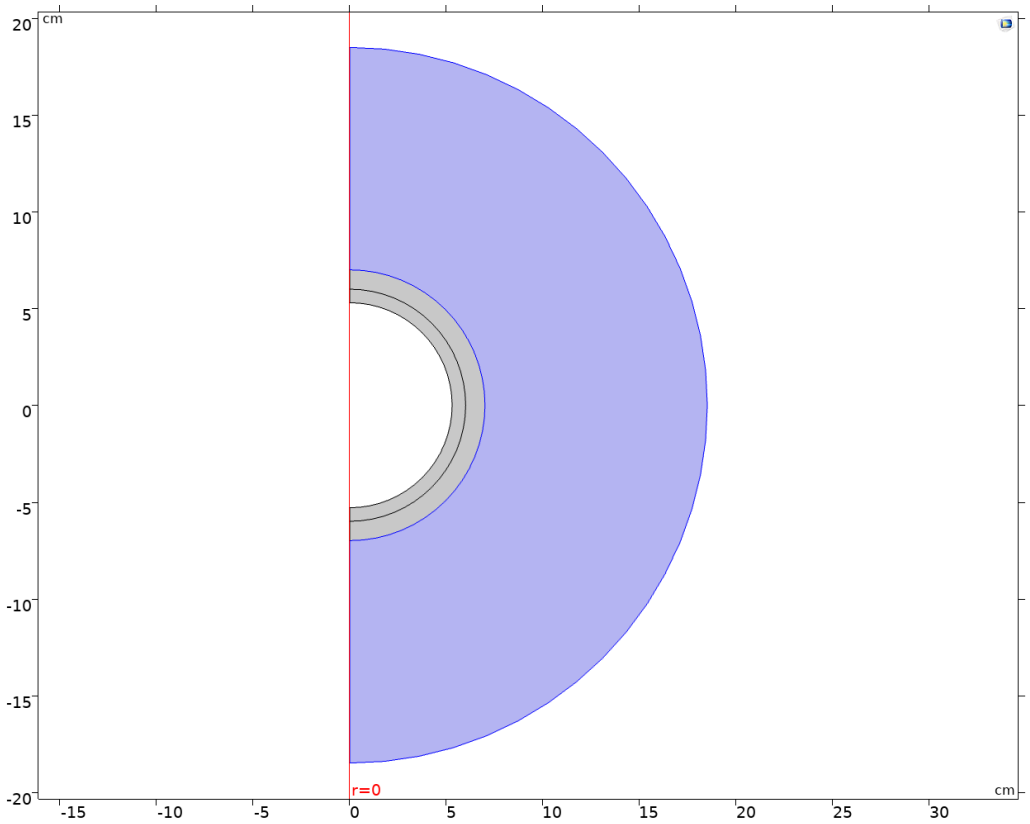
Case 2 Materials

- Fuel 2
  - Solid (no phase change)
  - k(T)
  - Density = constant
  - cp(T)
  - Source: AAA Fuels Handbook, Kim and Hofman



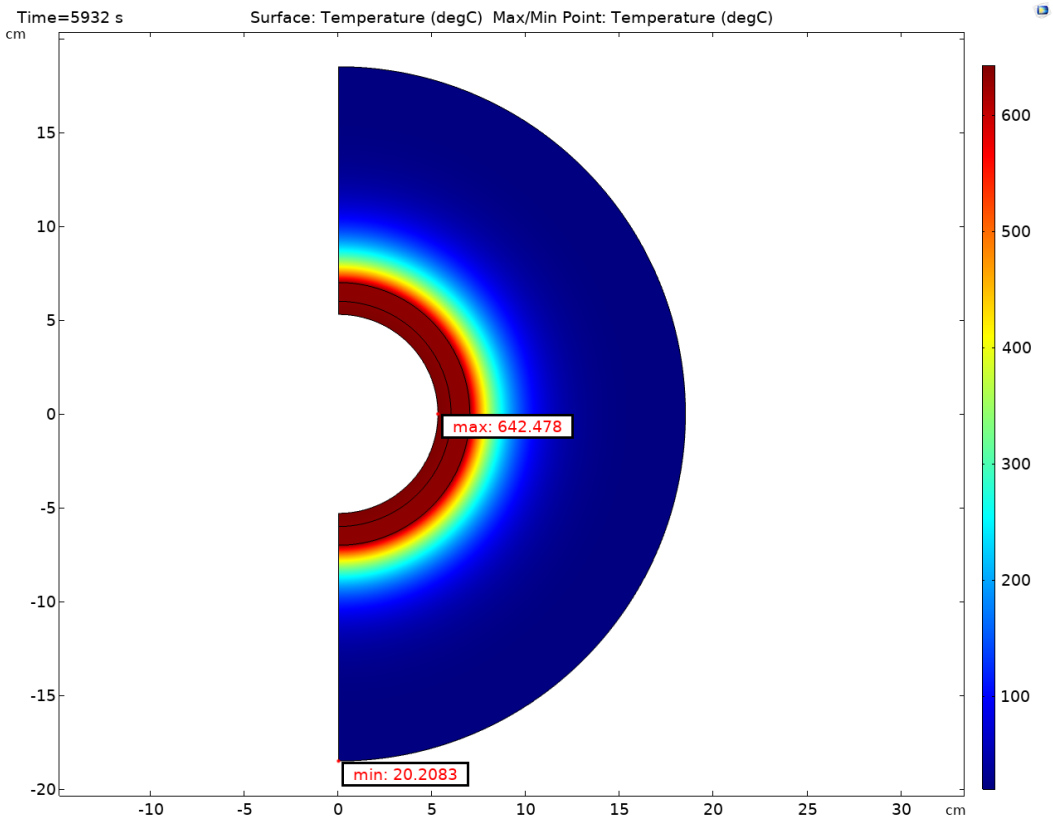
Case 2 Materials

- Low Tech Material
  - Solid (no phase change)
  - k(T)
  - Density = constant
  - cp(T)

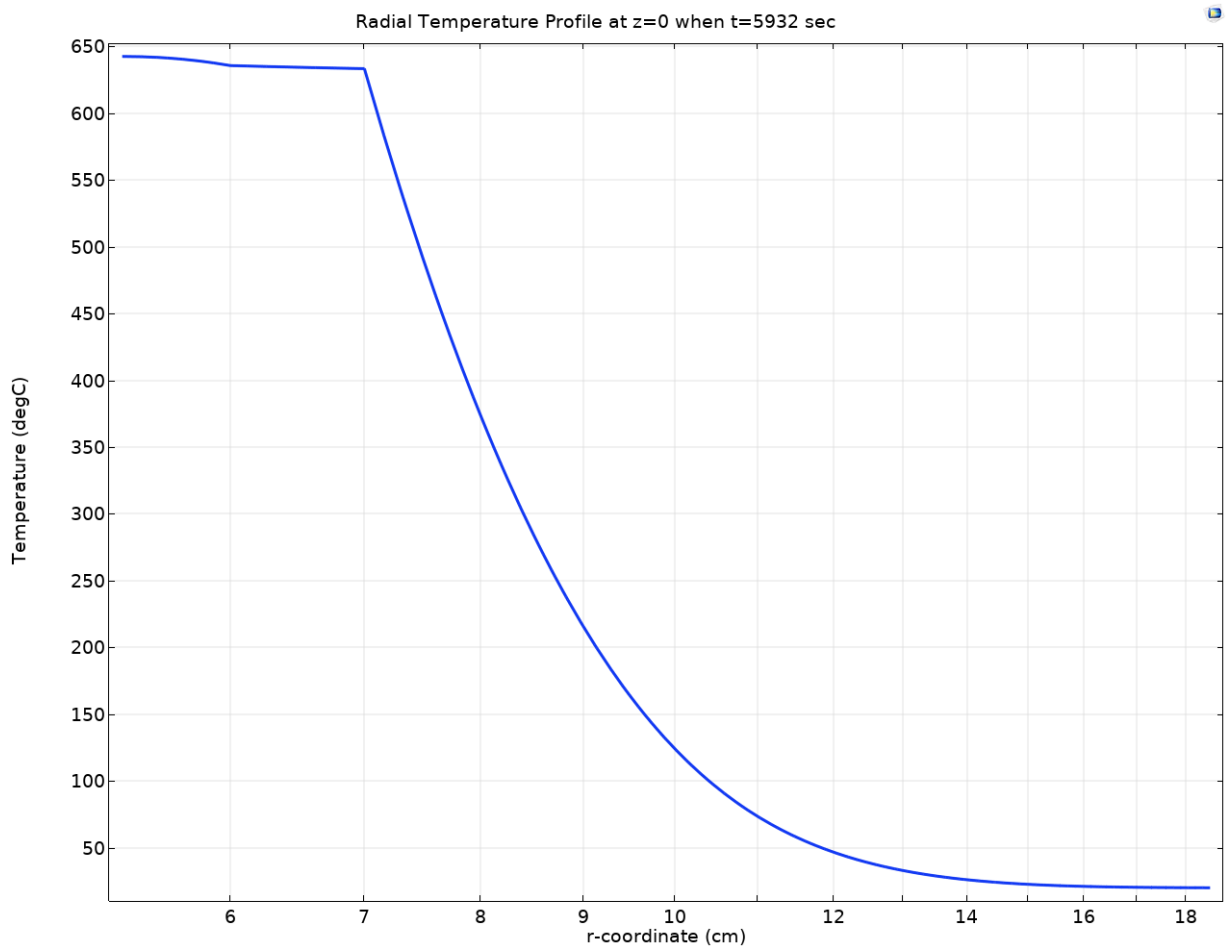


Results: Case 2- Air, Transient

- Transient Run
- Shell 1 Tavg= 640.00 degC at t=5932 sec.
- We would have a lot of melting in the low tech material before shell 1 reaches 640 degC. I would expect shell 1 to translate down into the melt and no longer be concentric with the surrounding shells.
- Low Tech Tmelt = 79 degC



Results: Case 2- Air, Transient

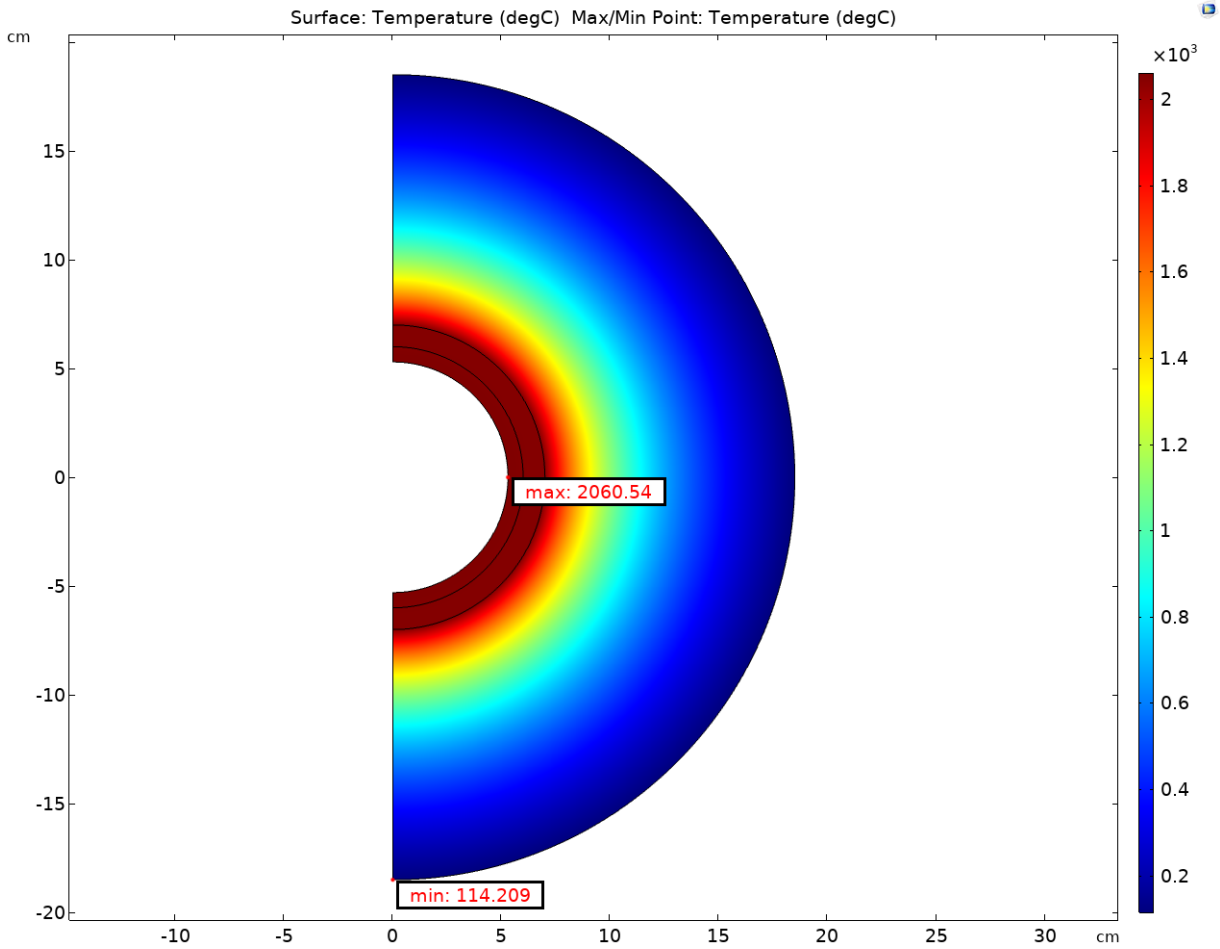


Results: Case 2- Air, Transient

- Why does Case 2 take longer to heat up compared to Case 1?
  - Thermal Resistance Circuit $R_{sphere} = \frac{r_1 - r_2}{4\pi r_1 r_2 k}$
    - Case 1: $R_{sphere_{total}} = 4.3 \frac{Kelvin}{W}$
    - Case 2: $R_{sphere_{total}} = 3.2 \frac{Kelvin}{W}$
    - Case 3: $R_{sphere_{total}} = 1.8 \frac{Kelvin}{W}$
  - Thermal Diffusivity $\alpha = \frac{k}{\rho * c_p}$
    - HDPE α = 10.1E-8 m^2/sec
    - Low Tech α = 9.6E-8 m^2/sec
    - High Tech α = 16.3E-8 m^2/sec

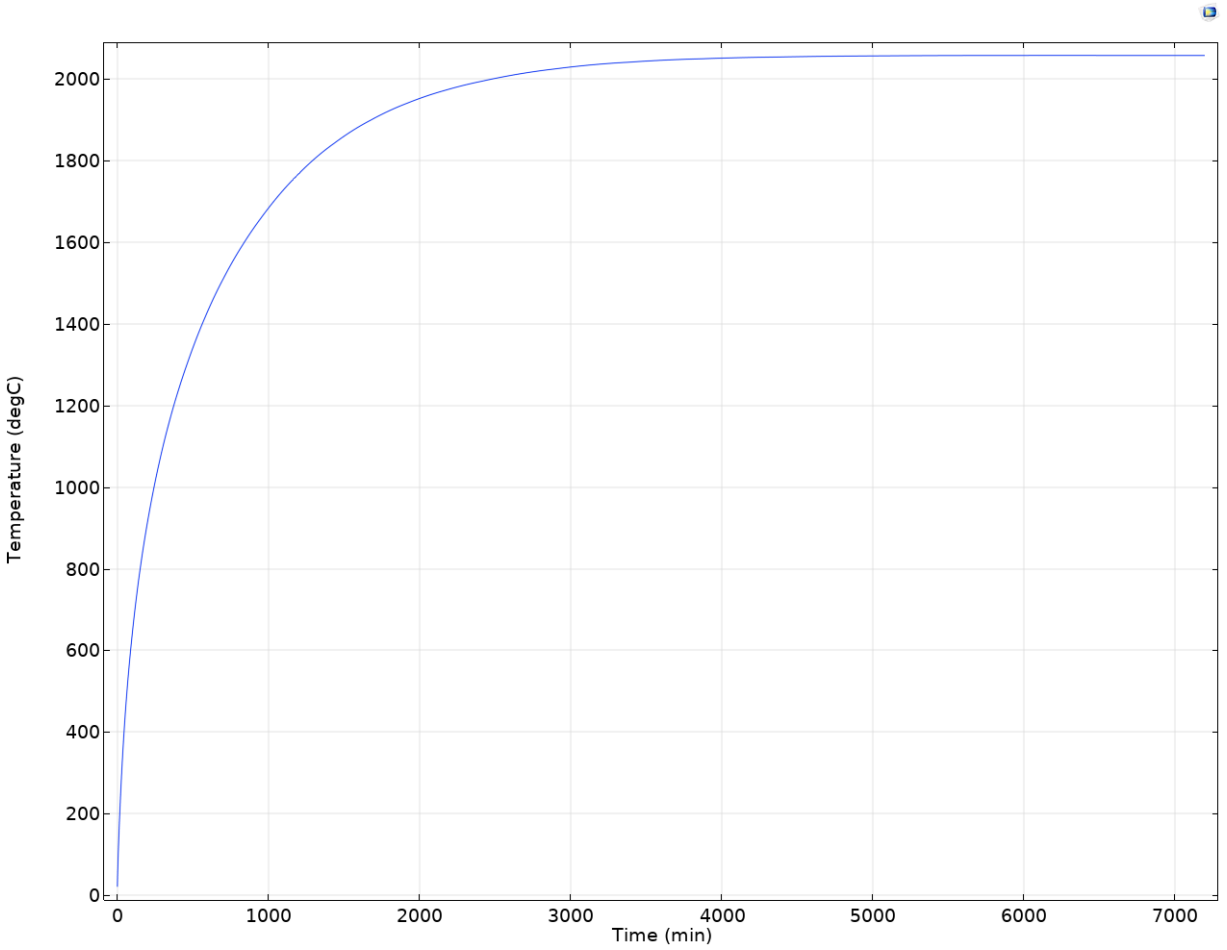
Results: Case 2- Air, Steady State

- Steady State Results for reference.
- ~2800 min = 46.6 hours to reach steady state (see next slide)



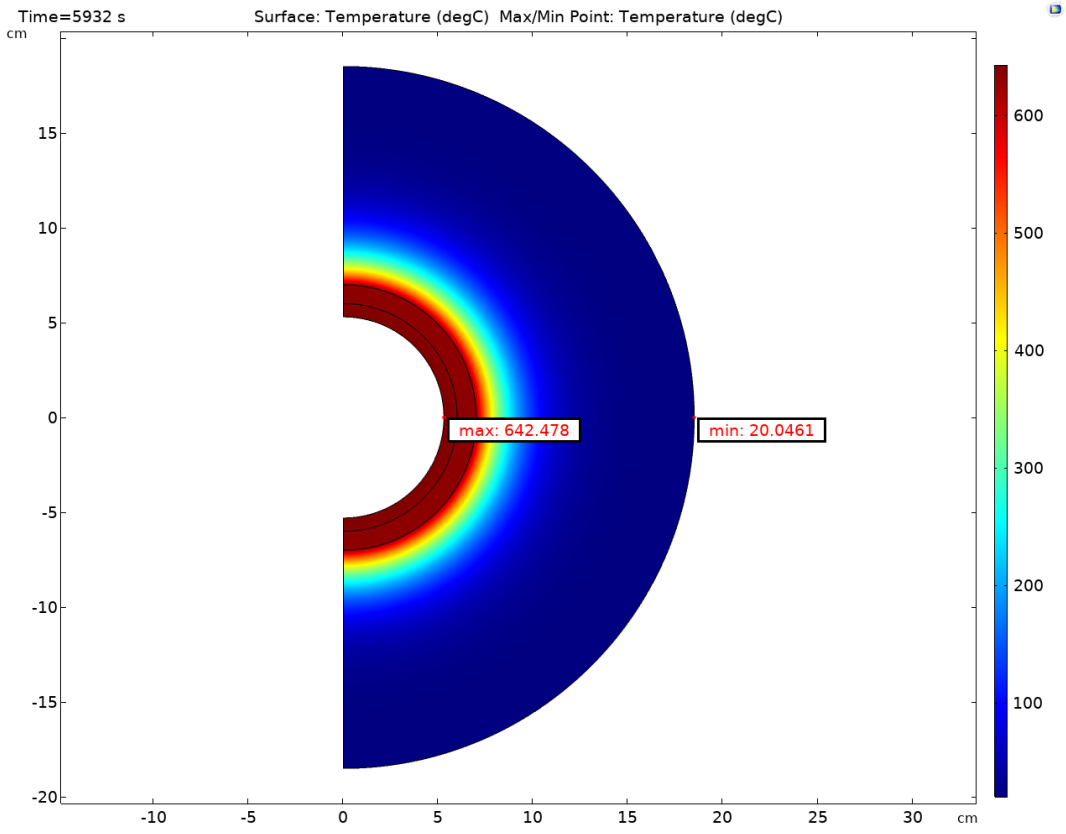
Results: Case 2- Air, Steady State

- Average Temperature in Shell 1 vs Time
- Time to reach 98% of steady state value = 2725 minutes



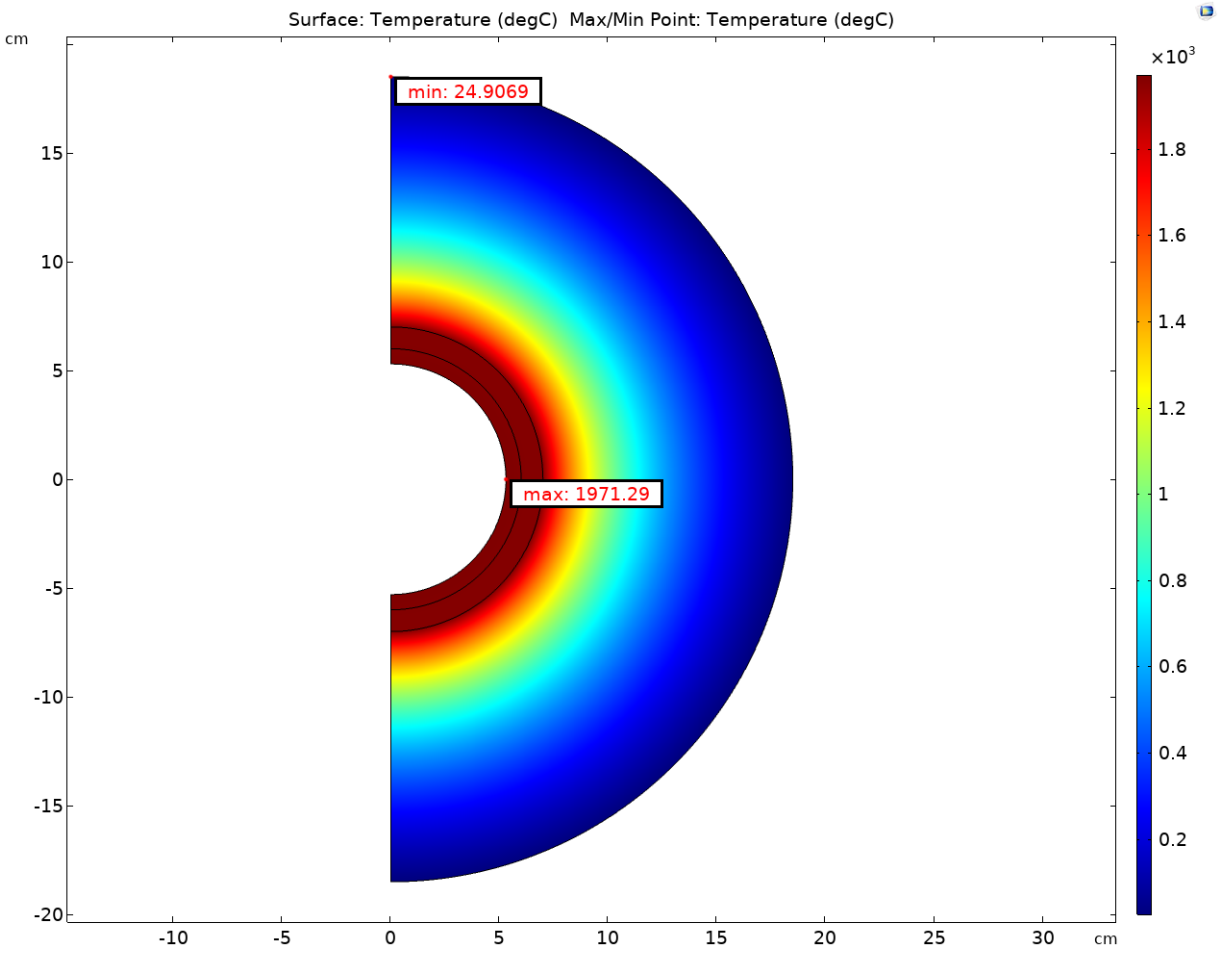
Results: Case 2- Water, Transient

- Transient Run
- Shell 1 Tavg= 640.00 degC at t=5932 sec. Exactly the same time as with air; this makes sense since the outer surface of shell 3 does not increase in temperature so any benefit of having a better heat sink is not “seen” by shell 1. The steady state results however will show the difference.
- The same melting comments apply as with air.



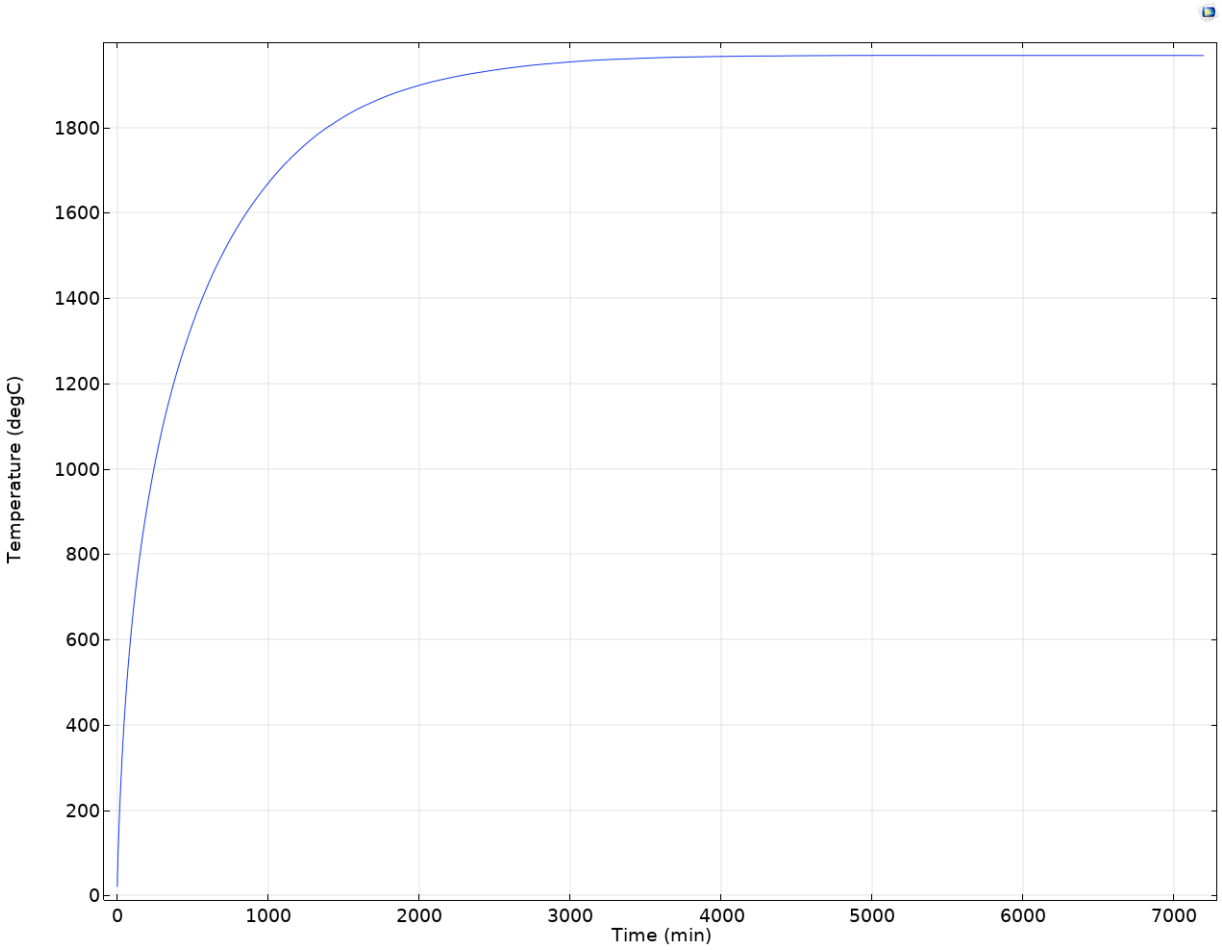
Results: Case 2- Water, Transient

- Steady State Results for reference.
- Notice how much cooler the outside surface of Shell 3 is due to the water.
- ~2400 min = 40 hours to reach steady state (see next slide)



Results: Case 2- Water, Transient

- Average Temperature in Shell 1 vs Time
- Time to reach 98% of steady state value = 2381 minutes

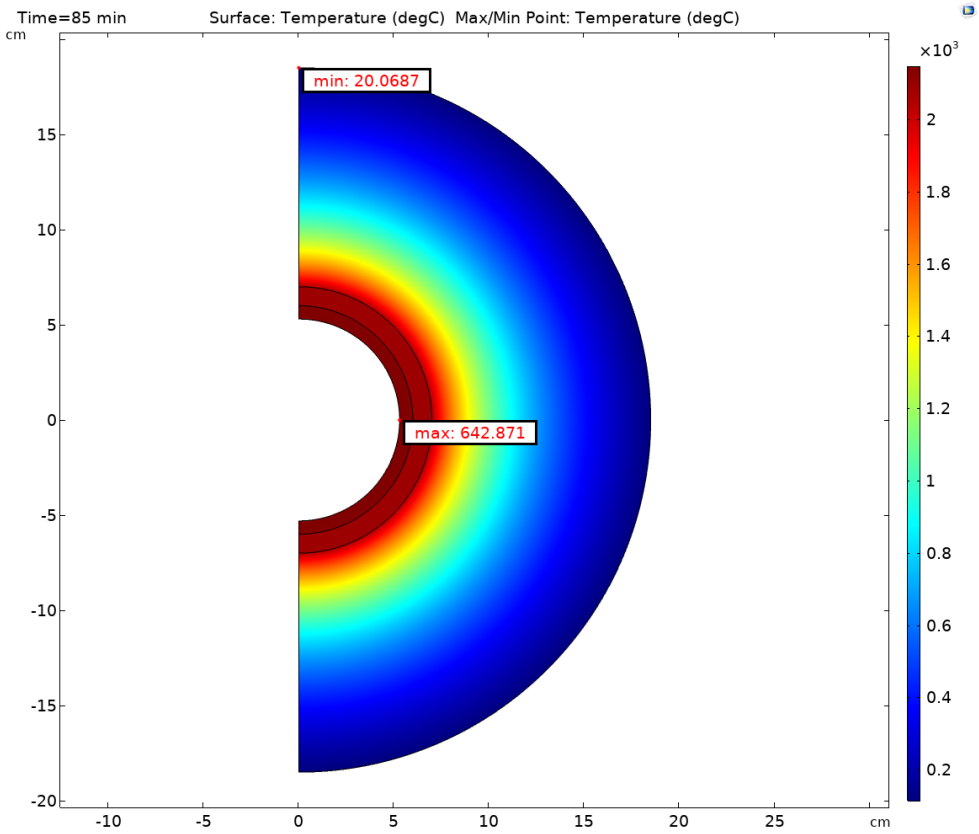


Case 2c Assumptions

- Added .0254 cm air gaps between shells 1 & 2 and 2 & 3.
- Added latent heat of fusion for melting of low tech material. Same case #s apply.

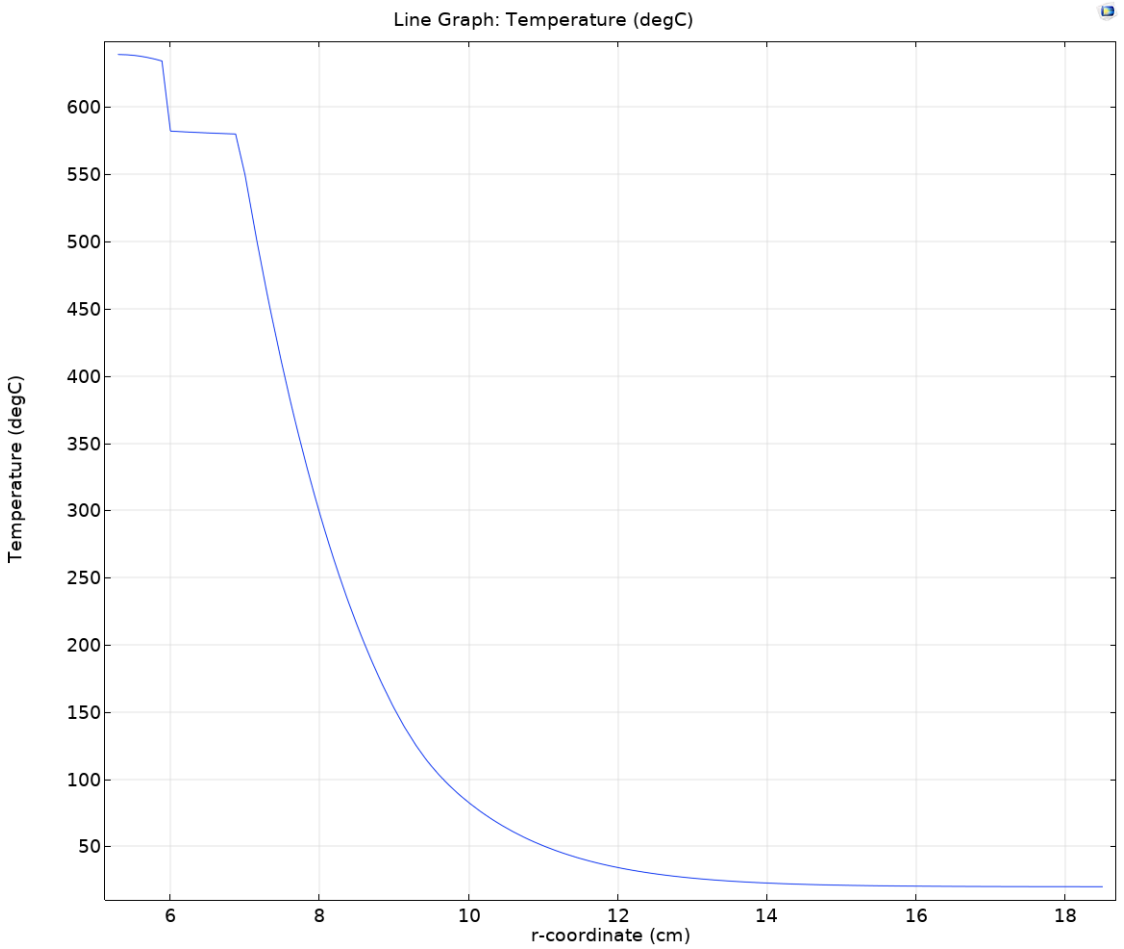
Results: Case 2c- Air, Transient

- Transient Run
- Shell 1 Tavg= 640.00 degC at t=85 min, less time than in case 2 due to the presence of the air gaps.



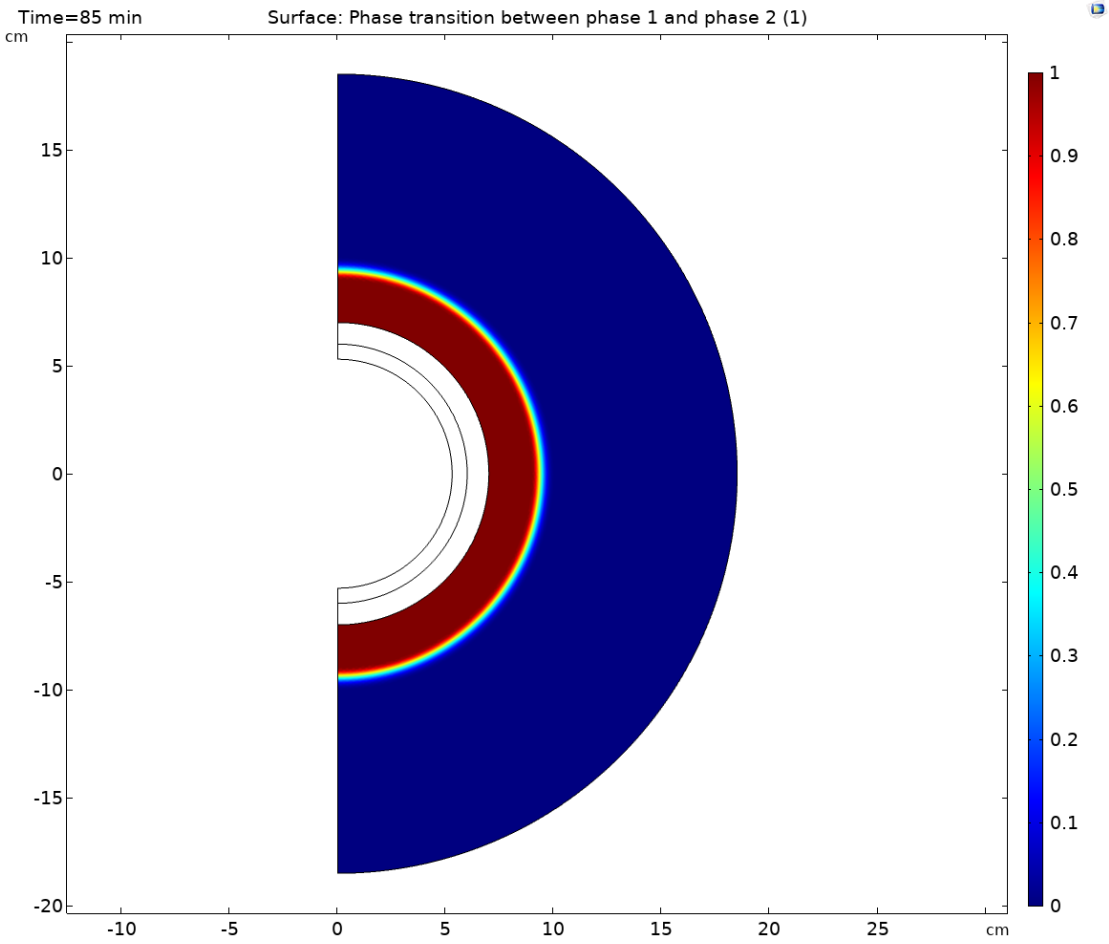
Results: Case 2c- Air, Transient

- Radial temperature profile at z=0 at t=85 min.
- Notice the large temperature gradient across the air gaps.



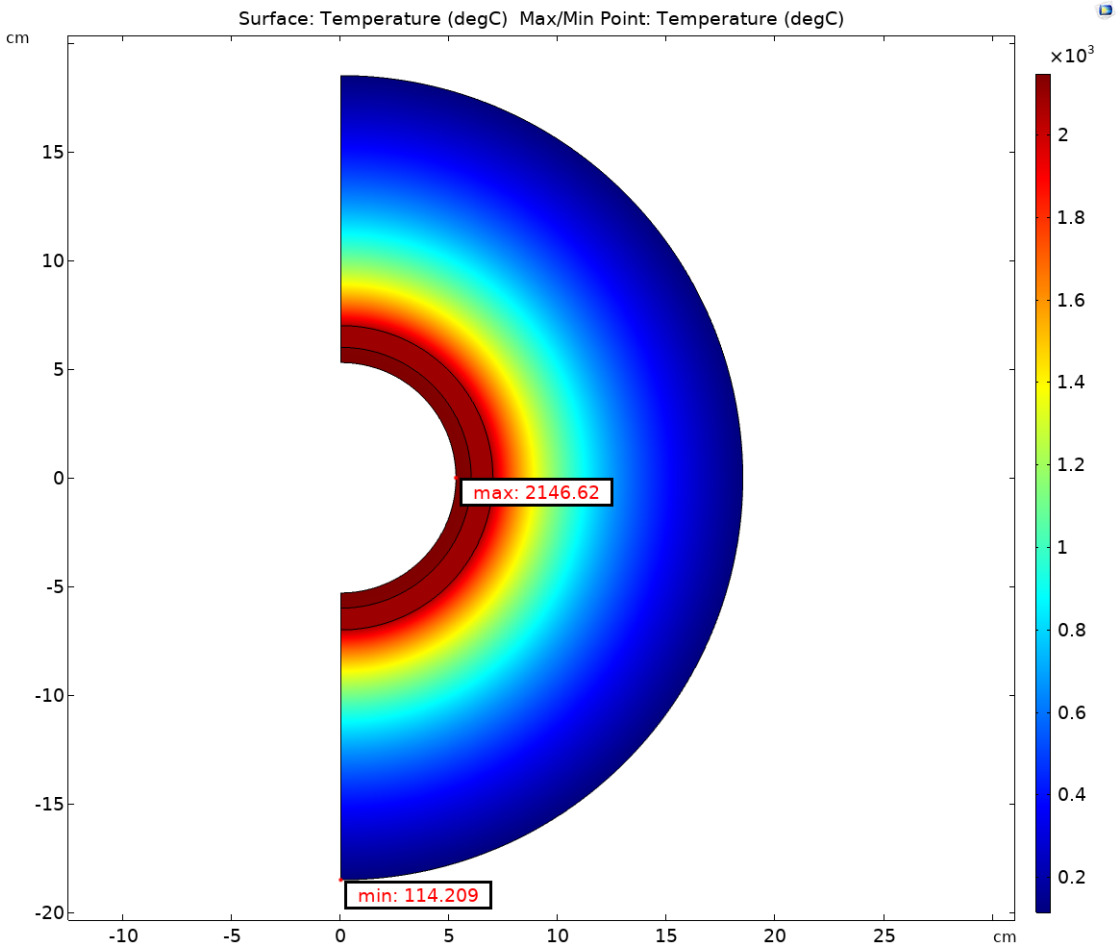
Results: Case 2c- Air, Transient

- Transient Run
- Shell 1 Tavg= 640.00 degC at t=85 min
- Phase fraction of the low tech material shown in the plot. A value of 1 indicates liquid while 0 is solid.
- Of course this assumes no mixing of the liquid phase and no movement of the shells. You can visualize shells 1 & 2 melting through the bottom of shell 3.



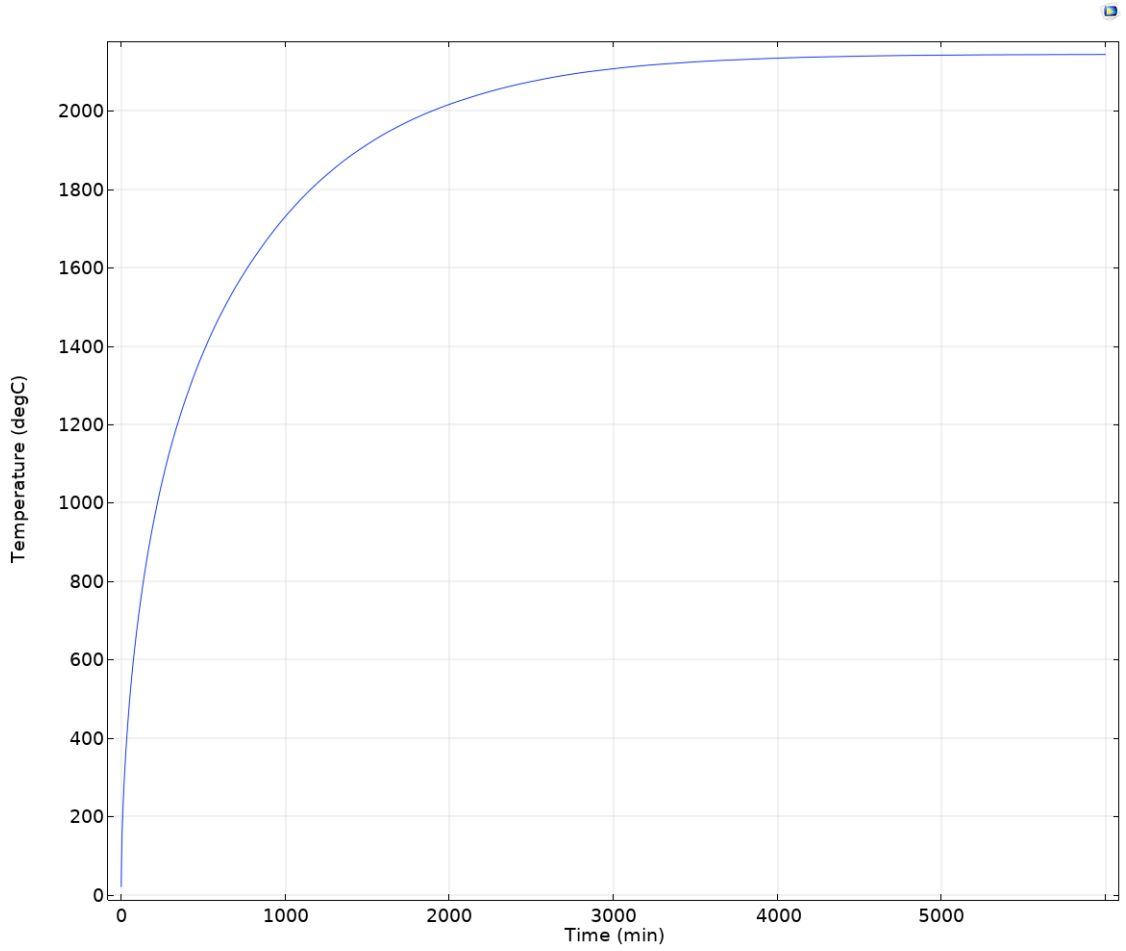
Results: Case 2c- Air, Steady State

- Steady State Results for reference.
- ~2900 min to reach steady state (see next slide)



Results: Case 2c- Air, Steady State

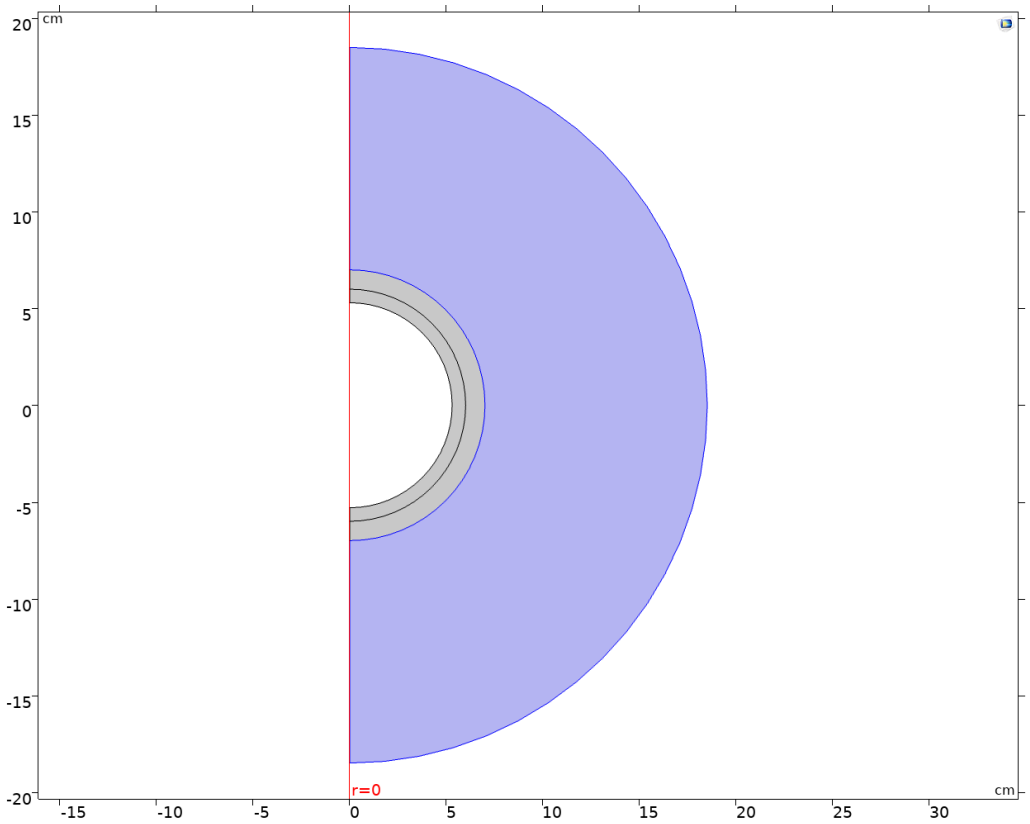
- Average Temperature in Shell 1 vs Time
- Time to reach 98% of steady state value = 2908 minutes



Case 3 Materials

- Same fuel material used in shell 1 & 2 as in case 2.

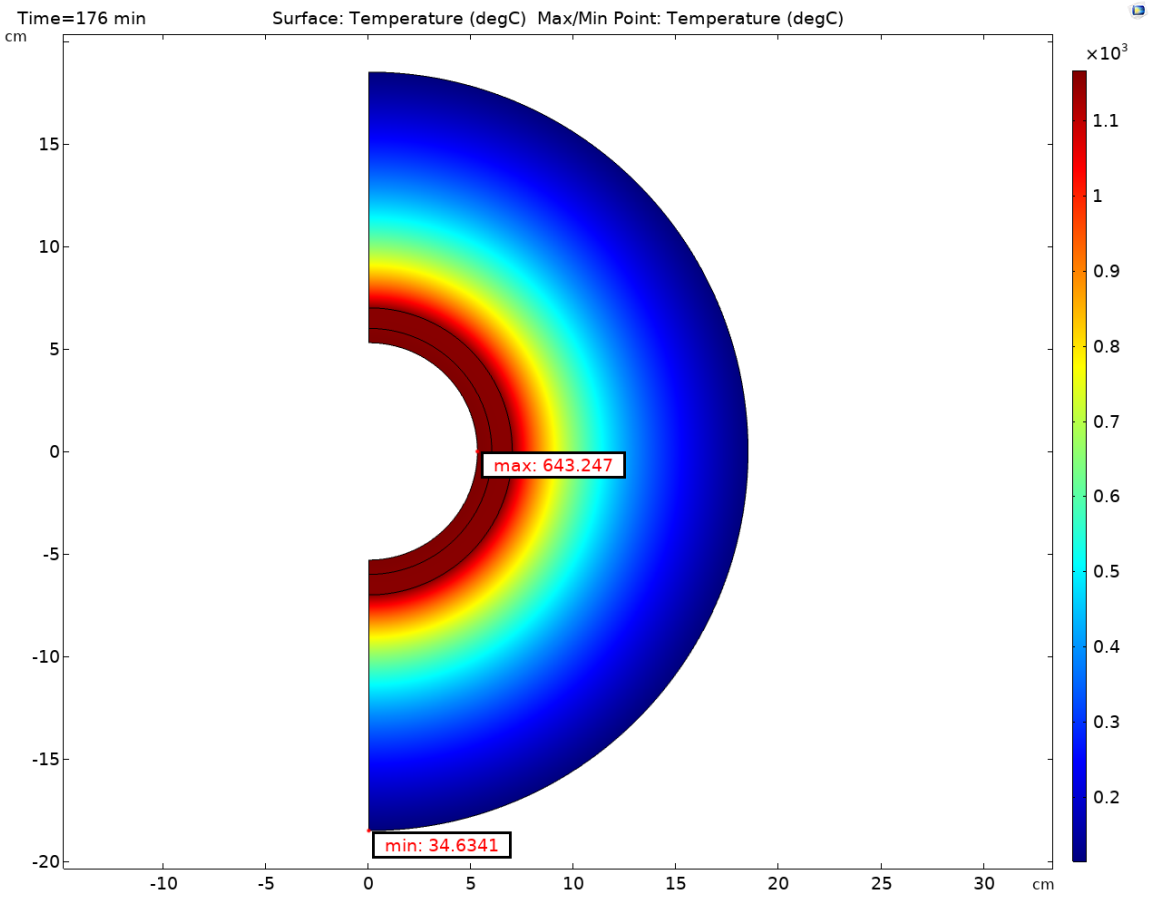
- High Tech Material
  - Solid (no phase change)
  - k(T)
  - Density = constant
  - cp(T)



Results: Case 3- Air, Transient

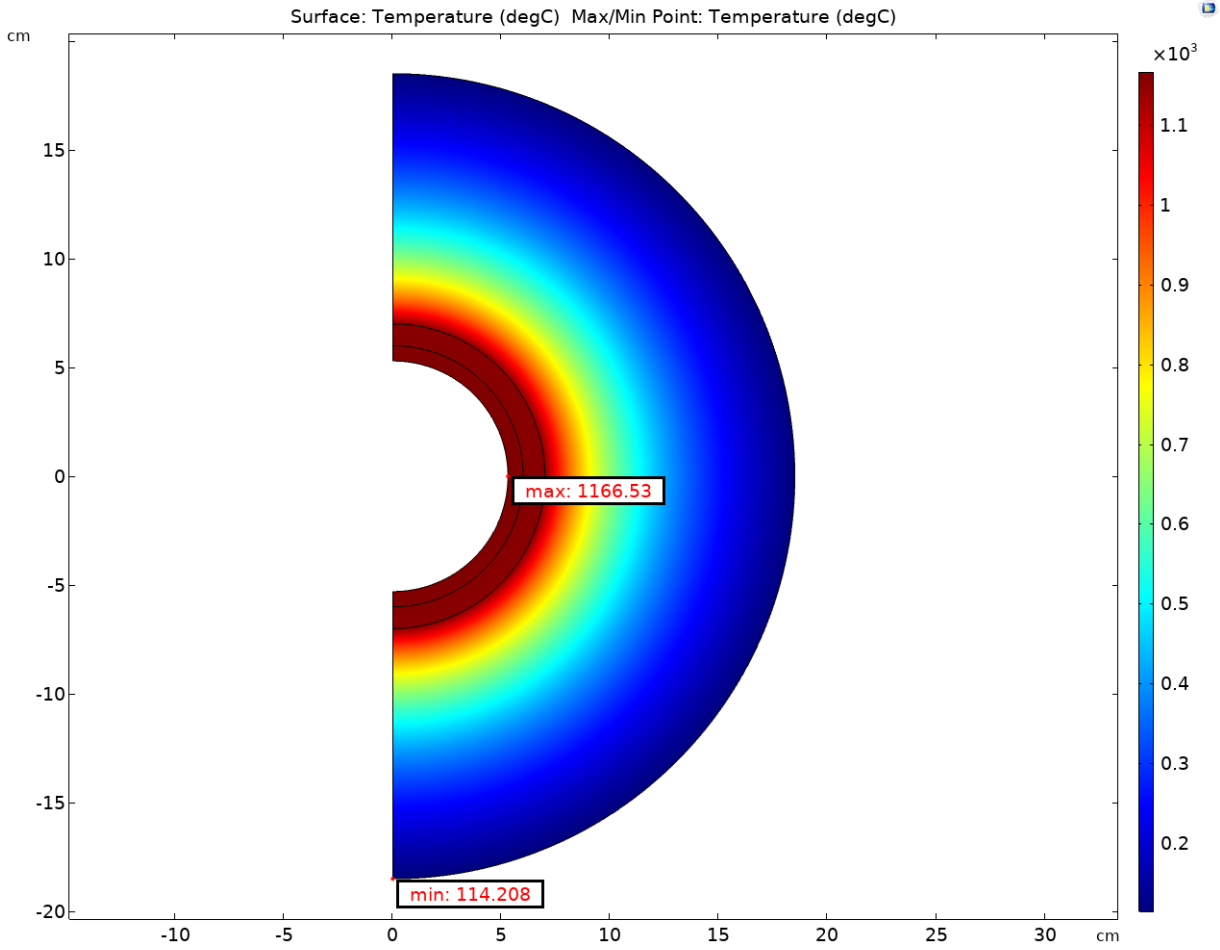
- Transient Run
- Shell 1 Tavg= 640.00 degC at t=10,560 sec.

- Outer surface of shell 3 heats slightly.
- High Tech Tmelt = 160 degC
- Enthalpy in Shell 1 = 92.1 J/g



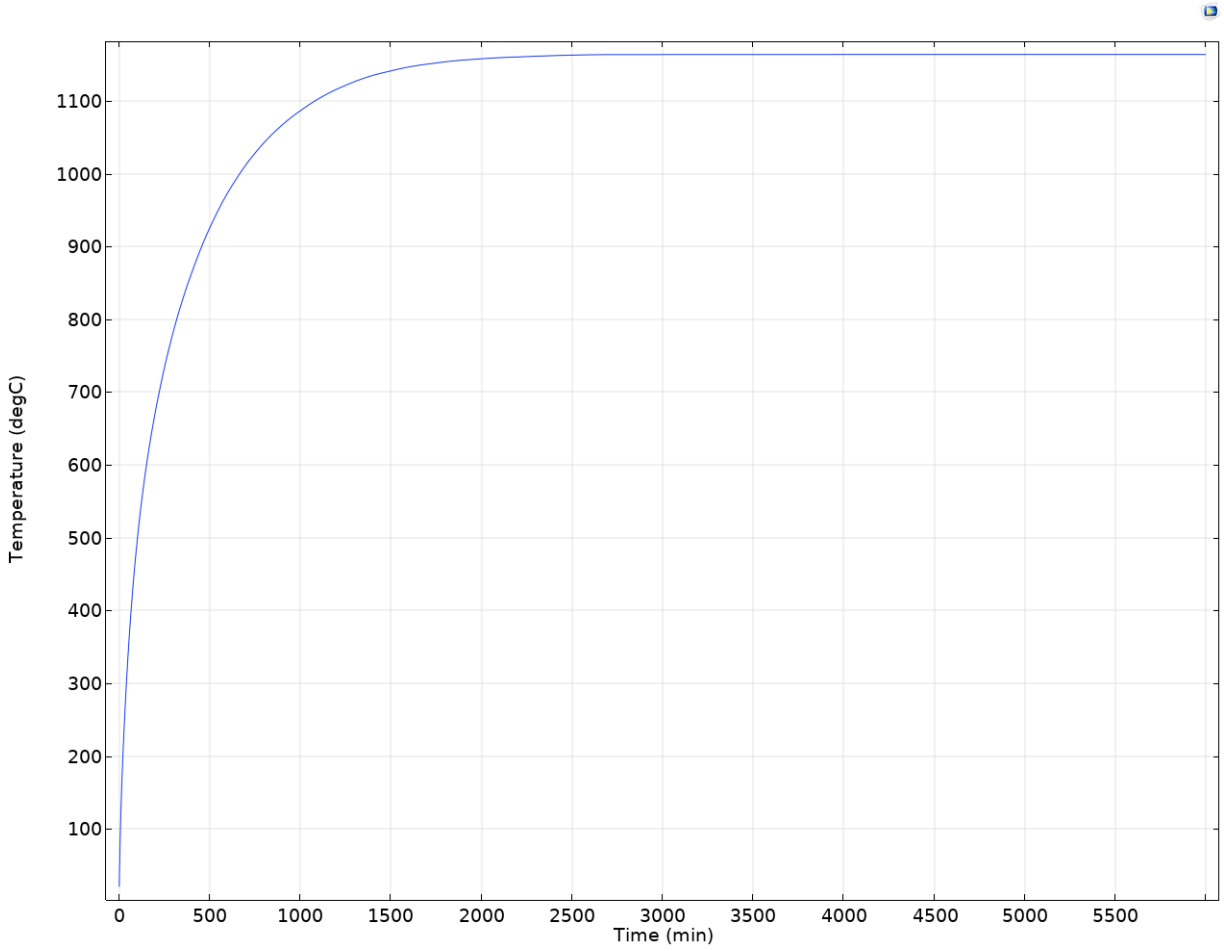
Results: Case 3- Air, Steady State

- Steady State Results for reference.
- High tech material has highest thermal conductivity compared to HDPE and Low Tech. This results in a lower steady state temperature in shell 1.
- ~1478 min = 24.6 hours to reach steady state (see next slide)



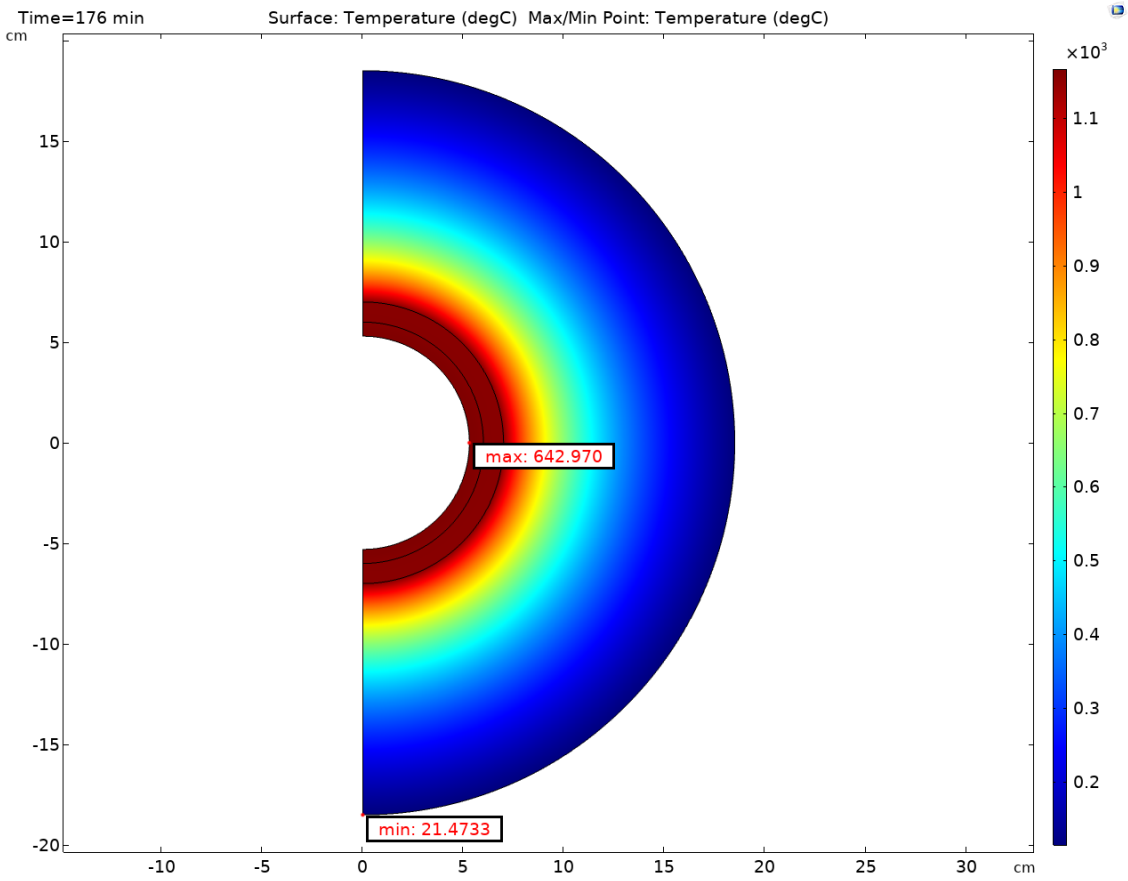
Results: Case 3- Air, Steady State

- Average Temperature in Shell 1 vs Time
- Time to reach 98% of steady state value = 1478 minutes



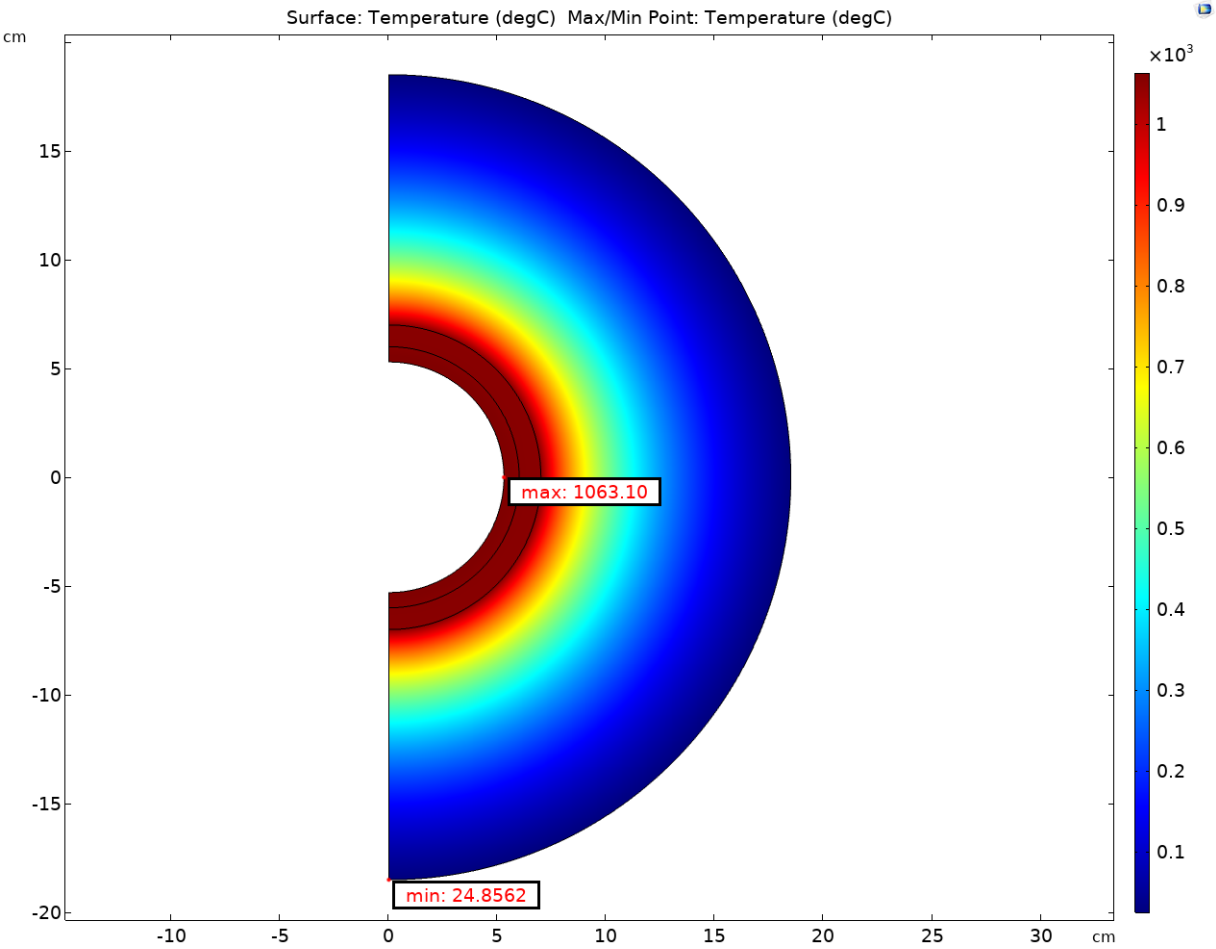
Results: Case 3- Water, Transient

- Transient Run
- Shell 1 Tavg= 640.00 degC at t=10,560 sec. Again, same time as with air.
- Outer surface of shell 3 is 13 degrees cooler than with air at t=176 min.
- High Tech Tmelt = 160 degC



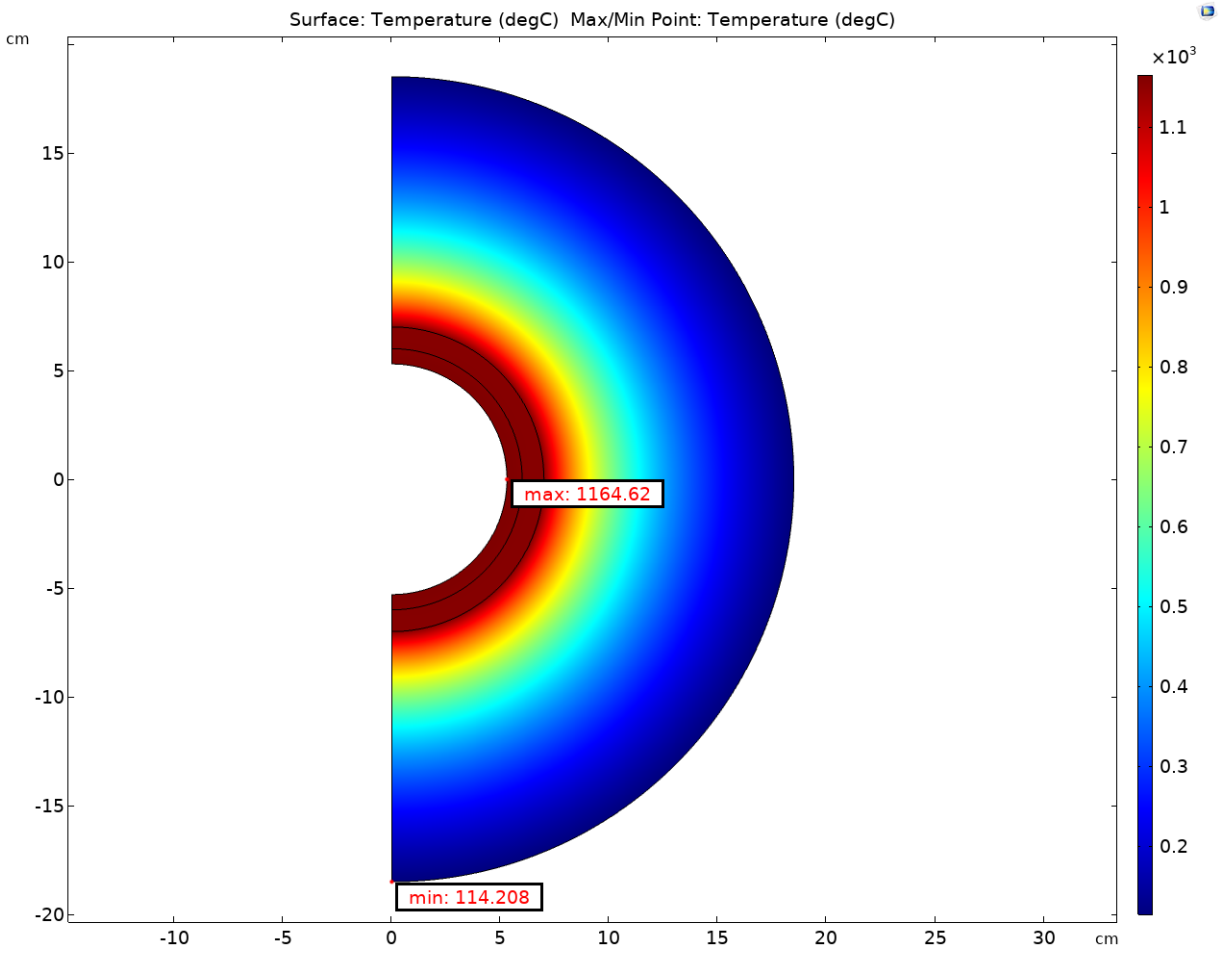
Results: Case 3- Water, Steady State

- Steady State Results for reference.
- ~1155 min = 19.25 hours to reach steady state



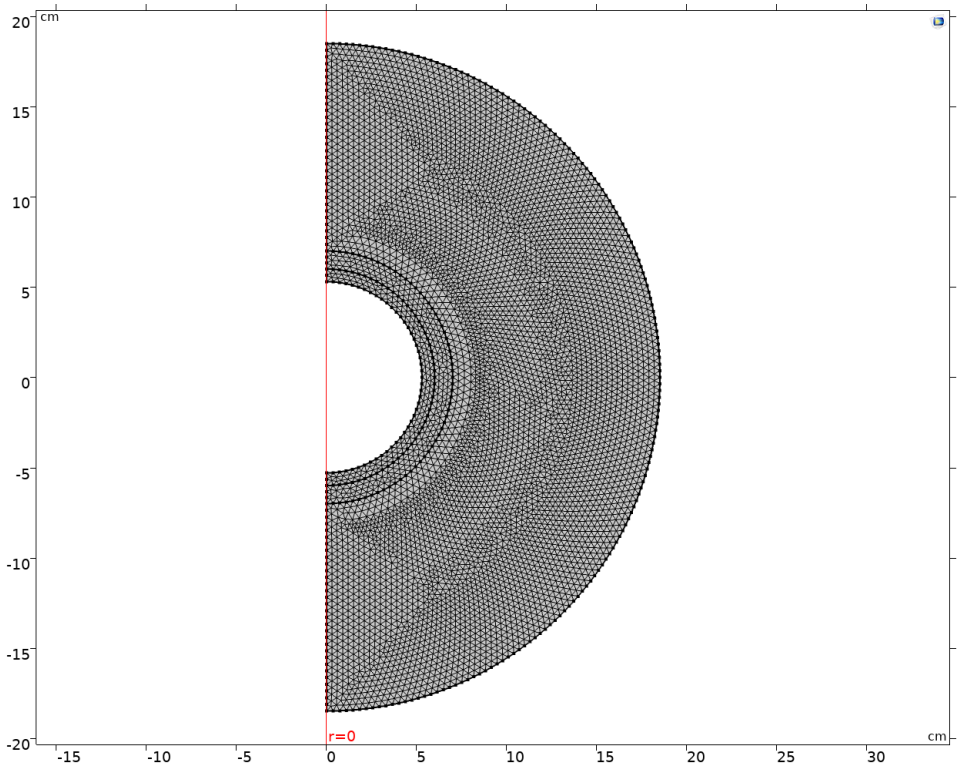
Results: Case 3b with new fuel 1 alloy, Air, Steady State

- Steady State Results for reference. Uses alloy of fuel 1.
- Constant material properties
- Maximum temperature is within 2 degC of Case 3 using elemental fuel 1.



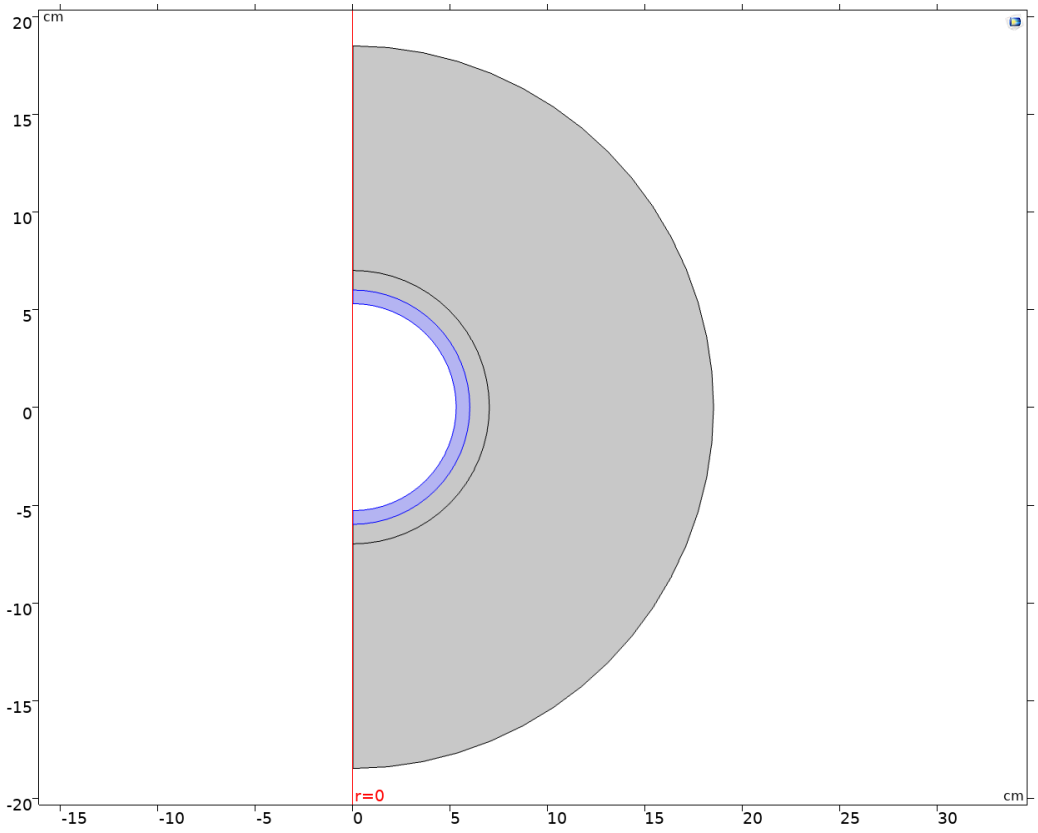
Case 4 Assumptions

- Shell 1 Initial Value = 640 degC at t=0
- Air gap (.0254 cm) between shells 1 & 2 and 3 & 4.
- No radiation heat transfer between shells
- The outer surface of shell 3 is a blackbody→ Perfect Emitter to surroundings
- Shell 1 is a solid→ No phase change
- Shell 3 is able to change phase→ Thermal properties change but no mass transport
- Isotropic thermal conductivity
- No thermal expansion
- Natural convection with air
- Laminar boundary layers



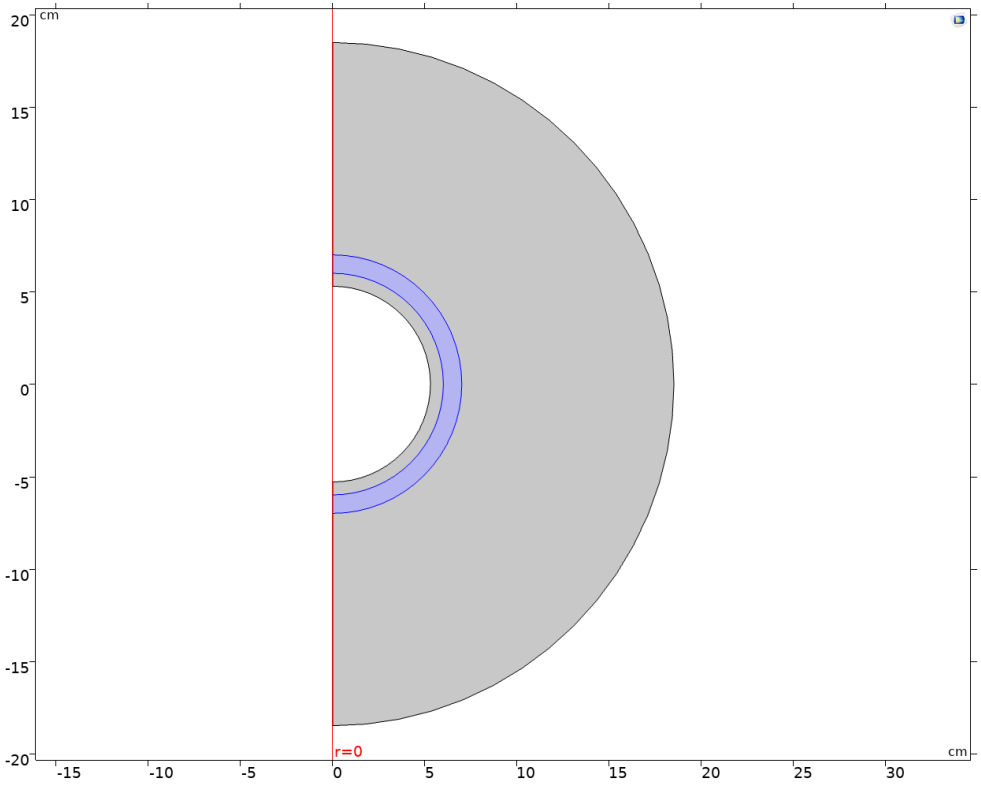
Case 4 Materials

- Fuel 1
  - Solid (no phase change)
  - Room temp solid phase used
  - k=constant
  - cp(T)
  - Density (T)
  - Source: AAA Fuels Handbook, Kim and Hofman



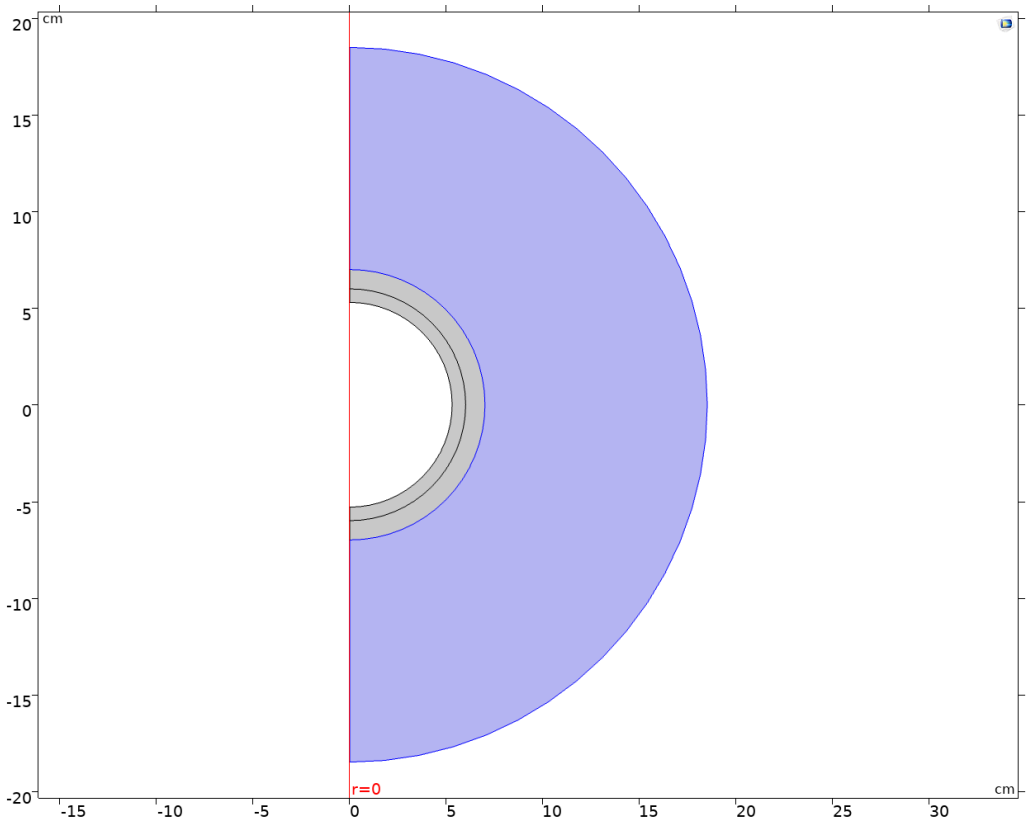
Case 4 Materials

- Fuel 2
  - Solid (no phase change)
  - k(T)
  - Density = constant
  - cp(T)
  - Source: AAA Fuels Handbook, Kim and Hofman



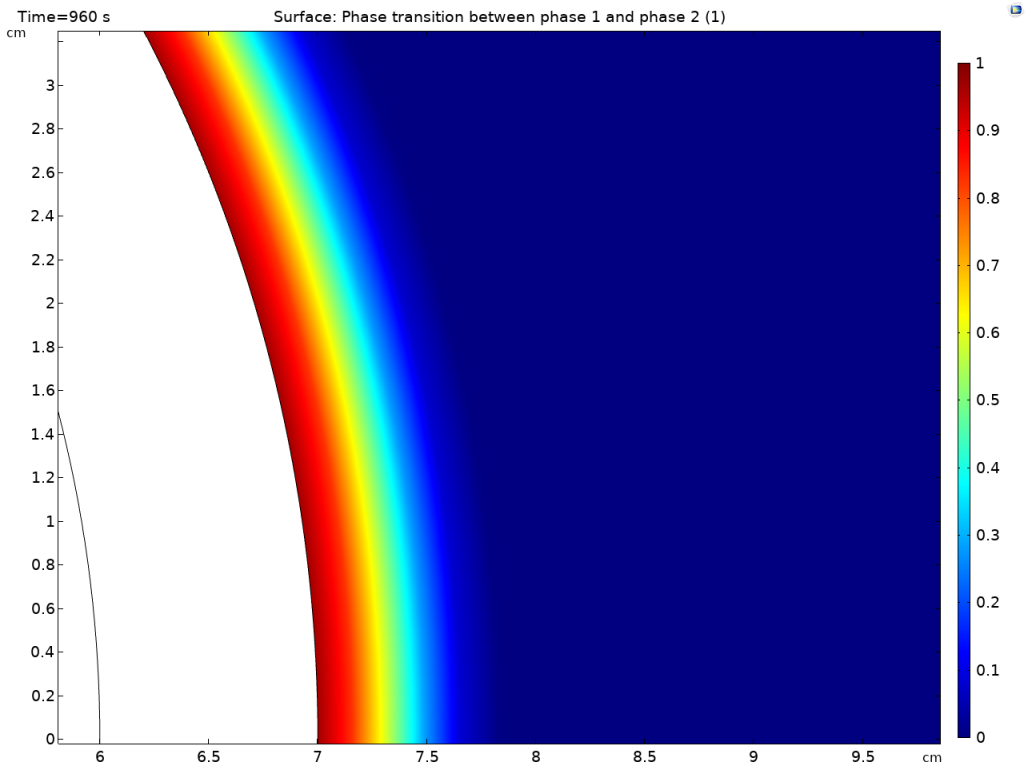
Case 4 Materials

- Low Tech Material
  - Solid or Liquid Thermal Properties
  - k(T)
  - Density = constant
  - cp(T)



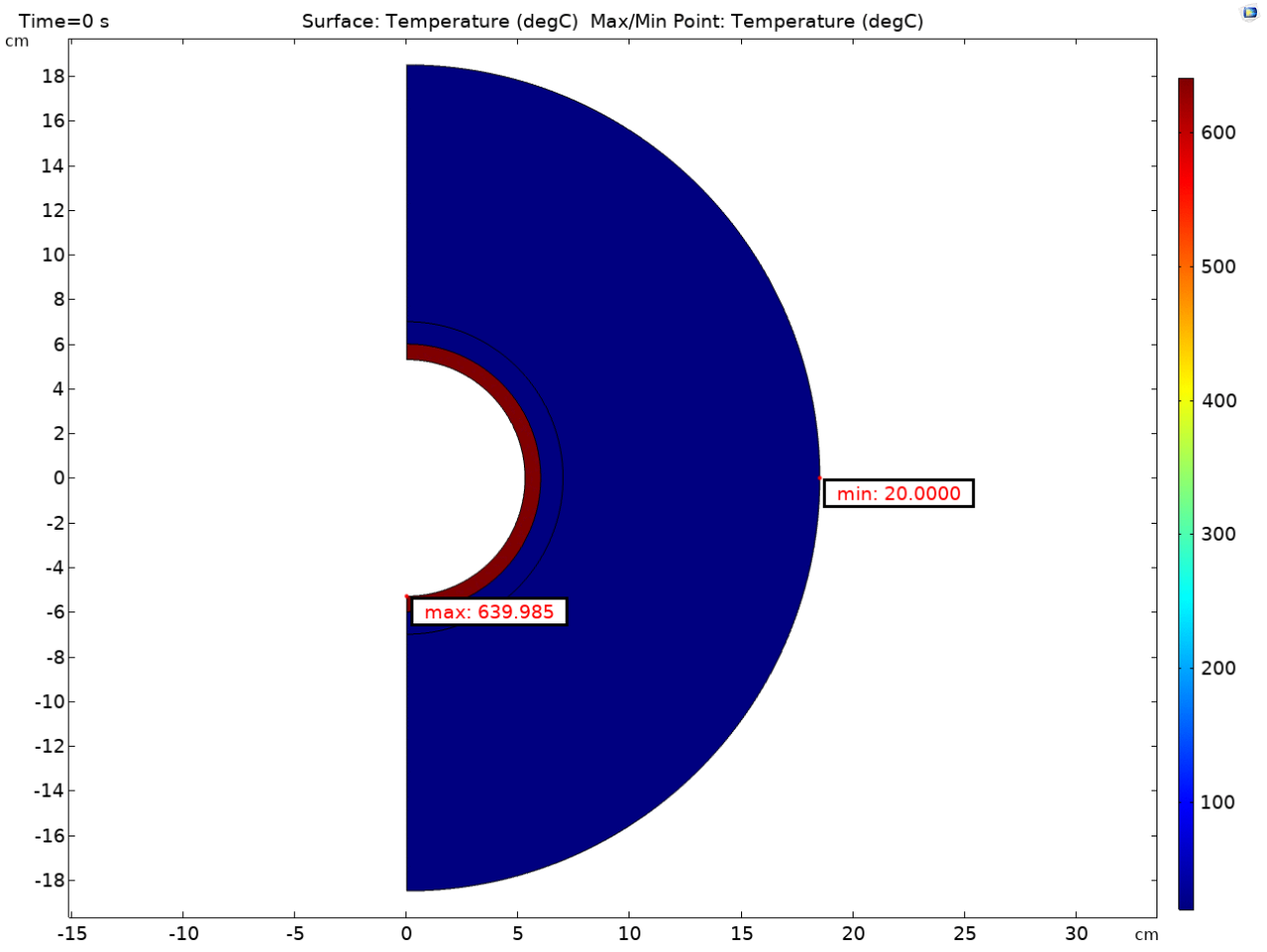
Case 4: Temperature and Phase Change Animation

- Time in animation is from 0→3600 sec.
- You can see that the low tech material softens for the first .5 cm maximum. Then it will solidify upon cooling.

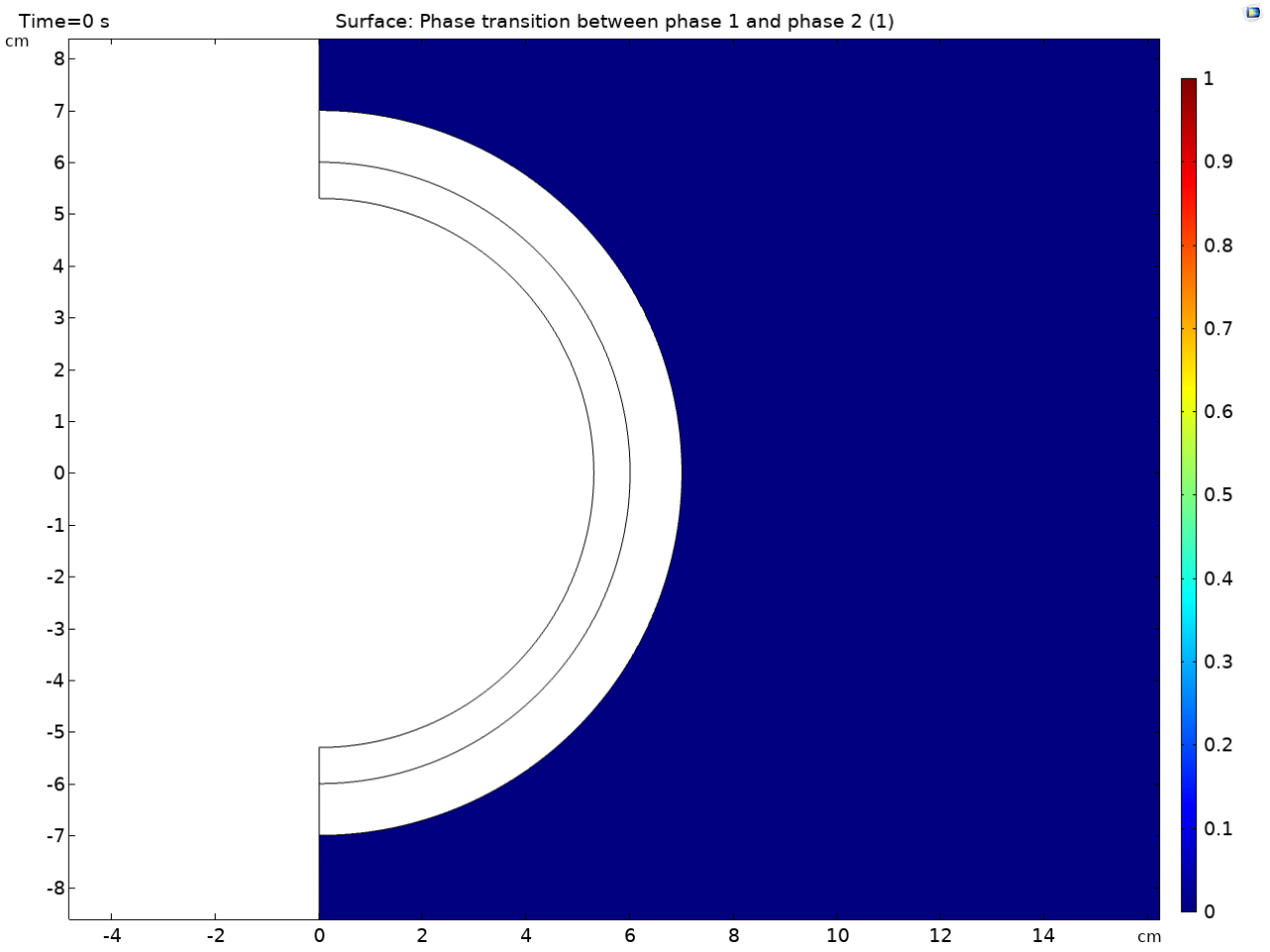


Phase fraction at t=960 sec. Phase fraction equals 1 for a liquid and equals 0 for a solid.

Case 4: Temperature Animation



Case 4: Phase Change Animation



Further Work

- Incorporate liquid/slush relocation (mass transport) during heat up
- Include heat transfer due to radiation between shells
- Anisotropic heat source

Conclusions

- In these ideal conditions, all simulations reached 640 degC in shell 1 for steady state conditions
- Transient times for the above were calculated